Hazard and Impact Scenario Development for Silicic Volcanoes in New Zealand

A Thesis submitted in fulfilment of the requirements for the Degree

of Master of Science in Disaster Risk and Resilience

by

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FRONTISPIECE

Aerial panorama of Lake Taupō and the surrounding region. Hidden beneath the Lake's surface is the Taupō Volcanic Centre, part of the wider Taupō Volcanic Zone in Aotearoa-New Zealand's central North Island (Credit: Dougal Townsend/GNS Science).

ABSTRACT

Aotearoa-New Zealand's (A-NZ) caldera volcanoes, located within the Taupō Volcanic Zone (TVZ) in the central North Island, have typically been characterised as a low probability, high consequence risk. These volcanoes are capable of a broad and complex range of geophysical activity creating multiple hazards of variable intensity, both spatially and temporally. These can have diverse, complex, and potentially severe impacts on society. Equally, the societal responses to such impacts, both potential and actual, can be just as diverse and driven by a complex variety of factors across social, cultural, economic, built, and natural environments – also spatially and temporally sensitive.

One important tool for disaster risk management is the development of scenarios, which can be used to illustrate one (of many) potential outcome(s) of a complex and highly variable system. By determining fixed values on otherwise uncertain inputs, it allows easier understanding of how a complete caldera unrest and/or eruption may unfold. The use of scenarios, built from a common framework, can allow exploration of the diversity of potential outcomes from the complex volcanic system that is the TVZ. This common framework, in turn, partially addresses a key limitation of the approach.

More recently, collaborative development of scenarios, jointly by scientists, practitioners and representatives for the community, has been used to create products which are both 'credible' (informed by robust scientific knowledge) and 'relevant' (useful and useable for end-users), and so can be considered 'legitimate' – where the scenarios reflect the various stakeholders' different values and priorities, and are ideally trusted by all and fit-for-purpose.

The aim of this thesis is to develop a modular, adaptable framework for the development of scenarios to underpin the management of A-NZ's caldera volcanic hazard risk within the ECLIPSE programme. This involves addressing the following objectives;

1. Identify and understand the hazards associated with silicic volcanoes in the Taupō Volcanic Zone.
2. Develop methods for disaster hazard and impact scenario development for silicic volcanism.
3. Evaluate the ECLIPSE Scenario Framework and ECLIPSE Scenarios through stakeholder engagement.

To achieve these objectives, an extensive literature review was undertaken to identify the hazards associated with caldera volcanoes in the TVZ and to identify potential methods for the development of volcanic scenarios. An inclusive co-production method was then used to identify and engage with key stakeholders, identify their respective requirements, and tailor the ECLIPSE Scenario Framework and ECLIPSE Scenarios to meet these requirements. Finally, the framework and scenarios were then evaluated in one-on-one interviews with stakeholders to assess the usefulness and useability of the framework and scenarios within the ECLIPSE community and the wider disaster risk management community.

The engagement workshops and interviews highlighted that the ECLIPSE Scenario Framework provided a useful foundation for combining cross boundary wants and needs from various stakeholder groups. Stakeholders stated that the ECLIPSE Scenario Framework (and ECLIPSE Scenarios) had given them a tangible output to structure discussions around caldera risk management from. They also stated it had provided guidance on where research should continue to develop in future, by highlighting research gaps – such as more in-depth social, cultural, and economic attributes and narratives within the ECLIPSE Scenario Framework and ECLIPSE Scenarios.

In summary, this thesis:

- Presents the first iteration of the ECLIPSE Scenario Framework – a framework for hazard and impact scenario development for silicic volcanoes in A-NZ.
- Presents two pillar scenarios developed from the ECLIPSE Scenario Framework as examples of how the framework can be used and what it can produce – ECLIPSE Scenario A: Taupō Unrest Scenario and ECLIPSE Scenario B: Taupō Eruption Scenario.
- Outlines a transparent, robust, co-production methodology for developing volcanic scenarios within A-NZ's caldera volcano risk management community.
- Provides recommendations for future development of caldera scenarios using the ECLIPSE Scenario Framework within both the ECLIPSE programme and the wider volcanic risk management community.

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List of Acronyms

AF8	Alpine Fault Magnitude 8 *A collaborative programme to save lives by planning and preparing a coordinated response across the South Island after a severe earthquake on the Alpine Fault using scientific modelling, response planning and community engagement.*
BoP CDEM	Bay of Plenty Civil Defence Emergency Management Group
CAG	Caldera Advisory Group
CDEM	Civil Defence Emergency Management
ECLIPSE	Eruption or Catastrophe: Learning to Implement Preparedness for Supervolcano Eruptions
ESDW	ECLIPSE Scenario Development Workshop
ESDLUW	ECLIPSE Scenario Development Lifeline Utilities Workshop
NZVSAP ESDS	New Zealand Volcano Science Advisory Panel ECLIPSE Scenario Development Session
ESFE Interviews	ECLIPSE Scenario Framework Evaluation Interviews
MCDEM	Ministry of Civil Defence Emergency Management (now NEMA)
NEMA	National Emergency Management Agency (formerly MCDEM)
NZVSAP	New Zealand Volcano Science Advisory Panel
Waikato CDEM	Waikato Civil Defence Emergency Management Group
VAB	Volcanic Alert Bulletin
VAL	Volcanic Alert Level
VEI	Volcanic Explosivity Index
VUI	Volcanic Unrest Index

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1 INTRODUCTION

1.1 RESEARCH CONTEXT

Aotearoa-New Zealand (A-NZ) sits at the boundary between the Pacific and Australian tectonic plates. This dynamic plate boundary results in A-NZ being home to several major natural hazards, from the Alpine Fault and the plate-boundary-related fault system in the South Island, to the active volcanic systems across the North Island (*Figure 1.1*), amongst other more frequent hazards such as storms, flooding, and landslides (National Emergency Management Agency (NEMA), 2007).

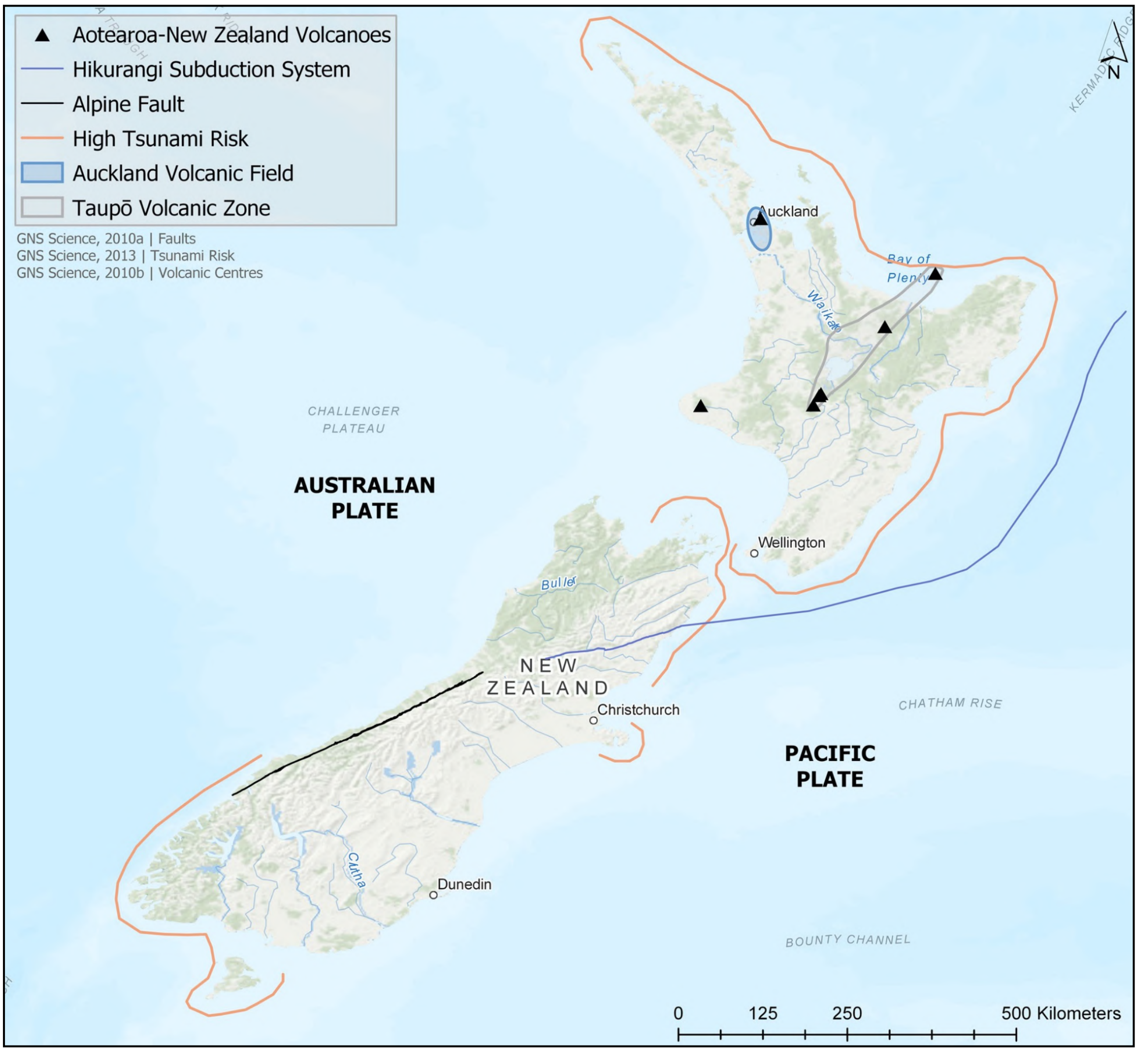

Figure 1.1: Aotearoa-New Zealand's seismic and volcanic hazardscape.

There are many factors across the natural, built, social, cultural, and economic environments (*Figure 1.2*) that cause these natural hazard events to become disasters. These events can result in serious disruptions to society and its functionality, which can cause significant social and economic capital loss (Ministry of Civil Defence Emergency Management (MCDEM), 2018). Given that society generally cannot control these events, developing an understanding of how these complex systems interact is potentially a key to success in disaster risk management.

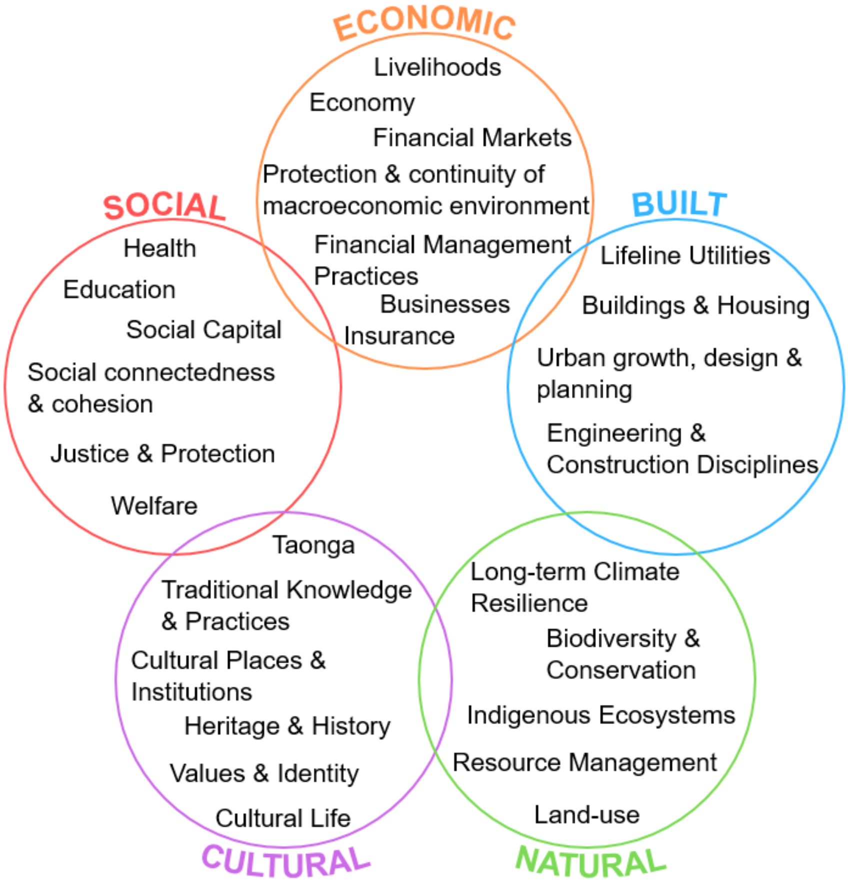

Figure 1.2: Resilience Environments that disaster risk management strategies work within in A-NZ. Adapted from the National Emergency Management Agency (NEMA)'s National Disaster Resilience Strategy (MCDEM, 2018).

A-NZ is home to just under five million residents, with just over one million of these residents located within the central North Island (Statistics New Zealand (StatsNZ), 2017a). In addition to the almost five million residents, hundreds of thousands of tourists visit annually, with over three million visitor arrivals across A-NZ in 2018 (StatsNZ, 2018). These tourists spent NZD$4.6 million in the Waikato and Bay of Plenty regions in 2019 (Ministry of Business, Innovation and Employment (MBIE), 2019a). The central North Island further provides a quarter of A-NZ's total renewable power generation through geothermal and hydro generation, accounting for approximately 15% and 10% of A-NZ's total renewable electricity generation respectively (MBIE, 2014a; Mercury, 2016). The central North Island also contributes to other significant industry exports, including dairying, forestry and horticulture and provides an important water reservoir for Auckland, A-NZ's largest city (Gillingham, 2008; GreatSights, 2014; StatsNZ, 2017b).

This abundance of activity surrounding A-NZ's central North Island, makes the Taupō Volcanic Zone (TVZ; *Figure 1.5*), a particular area of interest when investigating caldera volcano risk management in A-NZ. The TVZ is home to eight caldera centres, or "supervolcanoes", and is the world's most frequently active caldera system. Caldera volcanoes, which are depressions in the ground formed by the withdrawal and eruption of magma causing the roof of the magma chamber to collapse, are widely considered some of the most destructive volcanoes globally (*Figure 1.3*).

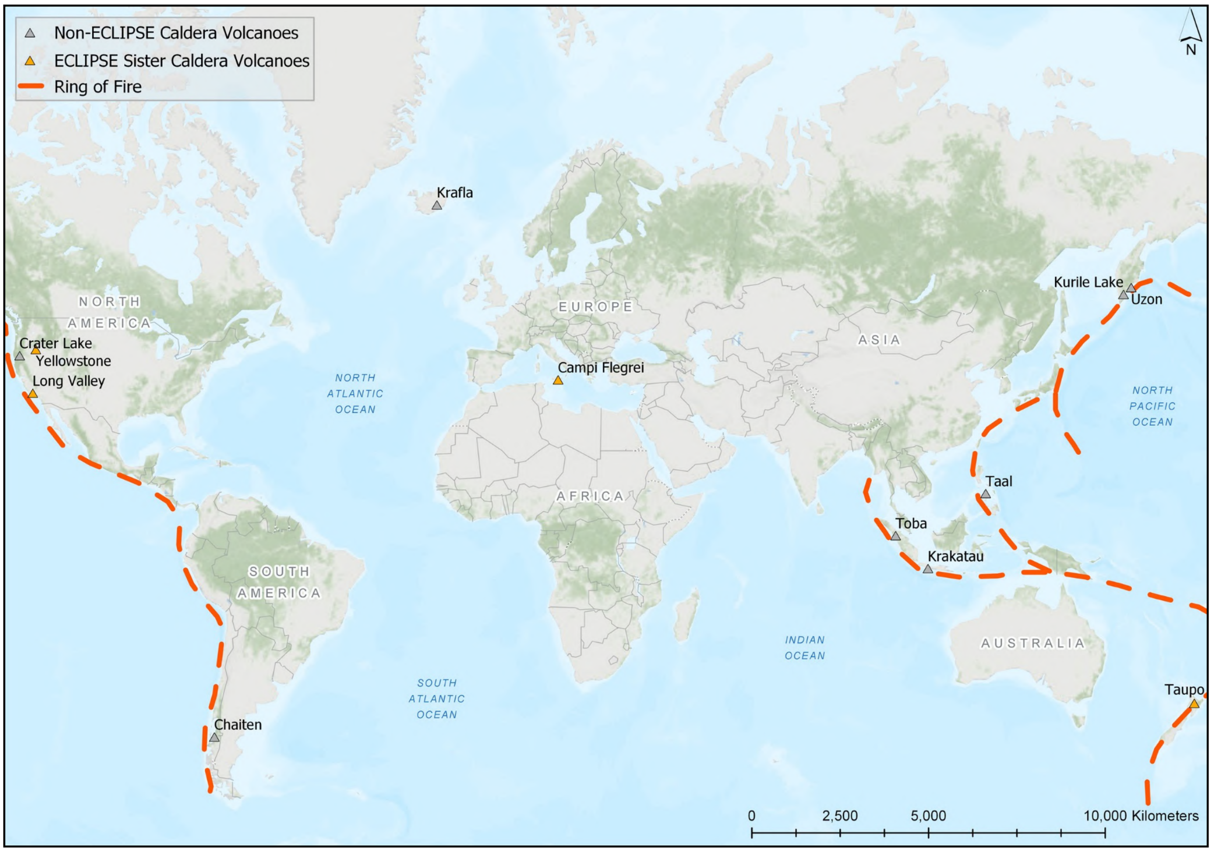

Figure 1.3: Notable caldera volcanoes across the world, including Campi Flegrei (Italy), Yellowstone (United States of America; USA), and Long Valley (USA), which are "sister volcanoes" to the Taupō Volcanic Centre (A-NZ) and the ECLIPSE programme.

Caldera volcanoes are also the largest and most unpredictable of A-NZ's volcanoes (Potter, Scott & Jolly, 2012; Barker et al., 2018). These volcanoes are characterised by frequent minor activity, such as earthquakes and geothermal system changes, with infrequent but moderate to large eruptions, including so called "super-eruptions". These caldera-forming super-eruptions can form craters 10-25km in diameter and deposit significant quantities of ash and pumice (collectively referred to as tephra) across the landscape. An example of this is the 26.5ka Oruanui eruption which represents one of the youngest caldera-forming events in the TVZ in A-NZ, consisting of pyroclastic flows that reached as far as 90km from the edge of Lake Taupō (Wilson, 2001).

Although these calderas are usually formed from one or two of these super-eruptions, their magma systems can also be the source of many comparatively smaller eruptions throughout their lifetimes. They can also experience periods of *disruptive volcanic unrest*, which is anomalous volcanic activity above normal background levels that is potentially, but not necessarily, precursory to an eruption; and periods of *quiescence*, gaps between eruptions with no or minimal background activity (Newhall & Hoblitt, 2002; Potter, Scott & Jolly, 2012). These periods of quiescence contribute to the challenge in understanding the processes involved with the build-up of magma necessary for caldera-forming events. The precursors to caldera-forming events remain elusive as they have rarely been witnessed, let alone documented by modern equipment (Potter, Scott & Jolly, 2012).

These caldera systems are complex, diverse, and present a wide range of hazards with potentially disastrous consequences. These systems are dynamic and sensitive to changes in and around them; most volcanic unrest at silicic caldera systems occurs in response to frequently experienced geologic phenomena, such as minor tectonic strain (Newhall & Dzurisin, 1988). As a result, forecasting the outcomes of these caldera events (unrest and/or eruption) is extremely difficult and there is no one simple solution to volcanic risk management (Newhall & Dzurisin, 1988).

One volcanic risk management approach, hazard and impact scenario development, has proven to be an effective disaster risk management tool, particularly within collaborative or co-produced research (Hayes et al., 2018; Oven et al., 2016; Johnston et al., 2000). Scenario development integrates knowledge from diverse disaster risk management domains and stakeholders throughout all development stages. This increases the credibility, relevancy, and legitimacy of outputs (scenarios) and nurtures more useful and useable products for relevant stakeholders (Boaz & Hayden, 2002; Tonini, Sandri & Thompson, 2015; Doyle et al., 2018; Loughlin et al., 2015).

1.1.1 The ECLIPSE Programme

This research is part of an Endeavour Fund research programme "*Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions*" (ECLIPSE). The Endeavour Fund is a Ministry of Business, Innovation and Employment (MBIE) fund that is an investment mechanism supporting research ideas with credible and high potential for positively transforming A-NZ's future (MBIE, 2019b). ECLIPSE is a five year MBIE-funded science programme with the strategic objective to use co-produced research to inform better management of risk from A-NZ's caldera volcanoes – which have been comparatively under-studied compared to the Auckland Volcanic Field (AVF) and the cone volcanoes (Mt. Taranaki, Mt. Ruapehu and Tongariro). The ECLIPSE programme brings together geological, geochemical and geophysical scientists, and applied disaster and social scientists, with key stakeholders such as GeoNet, Civil Defence Emergency Management (CDEM) Groups, and Iwi. The programme aims to use co-produced research to provide a sound science basis for the interpretation and response to unrest and possible eruption at A-NZ's caldera volcanoes (ECLIPSE, 2018).

1.2 Research Aims and Objectives

The aim of this thesis is to develop a modular, adaptable framework for the development of scenarios to underpin the management of A-NZ's caldera volcanic hazard risk within the ECLIPSE programme.

The specific objectives of this thesis were developed to ensure that the scenario framework development approach used co-production methods (outlined in *Chapter 2*) to undertake a transparent and inclusive process. This process identified the diverse range of potential stakeholders and their respective requirements, and tailored the ECLIPSE Scenario Framework and ECLIPSE Scenarios to most effectively meet these requirements. This adaptable framework will allow the scenarios to be updated as new science becomes available and as practitioner and policy requirements change. These objectives were to:

1. **Identify and understand the hazards associated with silicic volcanoes in the Taupō Volcanic Zone.**

This involved undertaking a hazard assessment (through literature review) in the TVZ and aligning it with and drawing similarities from global case studies of similar silicic systems.

2. **Develop methods for disaster hazard and impact scenario development for silicic volcanism.**

This was achieved through the development of a modular, adaptable hazard and impact scenario framework for A-NZ's caldera volcanoes. This objective was scoped through literature review and workshops held with stakeholders throughout the development process.

3. **Evaluate the Scenario Framework and scenarios through stakeholder engagement.**

The aim of this objective was to identify and use stakeholder and end-user wants and needs to help shape the scenario development. This was achieved through workshops with stakeholders throughout the development process and one-on-one interview evaluations at the end of the thesis.

These objectives were undertaken throughout the scenario framework development process and the conceptual workflow in *Figure 1.4* illustrates this process. The workflow demonstrates how the "build and review" phases, that link to Objectives Two and Three, were the main part of the research, focusing on utilising co-production and collaborative approaches to develop the scenario framework and scenarios.

Figure 1.4: ECLIPSE Scenario Framework development process phases illustrated with major engagement activities and the research project's timeframe.

1.3 Thesis Structure

This chapter, *Chapter 1*, introduces the thesis and establishes the context for this study. Firstly, silicic volcanism, its impacts on A-NZ, and the risk it creates are described. Then, disaster risk management at global and local scales is outlined, before volcanic risk management is introduced. Finally, a literature review on scenarios, as a tool for disaster risk management in A-NZ, are described, alongside literature addressing how frameworks for scenarios can be developed. This chapter addresses Objective One.

Chapter 2 outlines the development approach behind the ECLIPSE Scenario Framework and ECLIPSE Scenarios. This begins with a literature review of traditional disaster risk management approaches and outlines the conceptual disaster risk management framework used to guide this research. The second part of *Chapter 2* further describes the various stakeholder engagement workshops, discussions, and interviews undertaken throughout the thesis that were used to inform and evaluate the ECLIPSE Scenario Framework and ECLIPSE Scenarios. *Chapter 2* addresses part of Objective Two.

The first part of *Chapter 3* presents the results from the various stakeholder engagements undertaken throughout the research, while the second part outlines discussion and analysis of those findings and how they shaped the development of the ECLIPSE Scenario Framework. The third part of *Chapter 3* addresses the ECLIPSE Scenario Framework itself, with the fourth part of *Chapter 3* presents the evaluation from stakeholders through the results from the one-on-one interviews. *Chapter 3* addresses part of Objectives Two and Three.

Chapter 4 outlines the two ECLIPSE scenarios developed from the ECLIPSE Scenario Framework as part of this research, including the justification for each scenarios' development and the hazards and impacts included in the scenarios. *Chapter 4* addresses part of Objectives Two and Three.

Chapter 5, which addresses Objective Three, discusses the conclusions from this thesis research (including implications of the research), the limitations of the ECLIPSE Scenario Framework (and ECLIPSE Scenarios), and the future recommendations beyond this research project.

1.4 Silicic Volcanism in Aotearoa-New Zealand

This section of *Chapter 1* addresses Objective One; to undertake a hazard assessment, through literature review, in the TVZ and aligning it with and drawing similarities from global case studies of similar silicic systems. This section starts by characterising the TVZ, its caldera volcanoes, and the hazards presented by these volcanoes.

A-NZ's North Island sits upon the boundary of the Pacific and Australian tectonic plates, with the Pacific plate being subducted westward beneath the Australian plate. The partial melting of the subducting Pacific plate has caused magma to accumulate over millions of years under the central North Island and form a volcanic arc, whose surface expression is the TVZ. The TVZ stretches from Mt. Ruapehu in the south to Whakaari/White Island in the north (*Figure 1.5*), and is composed of several volcanic features, ranging from predominantly andesitic stratovolcanoes at the southern and northern ends of the zone, to silicic volcanic centres, known as caldera volcanoes, in the central section (Nairn, 1993; GNS Science, 2010b).

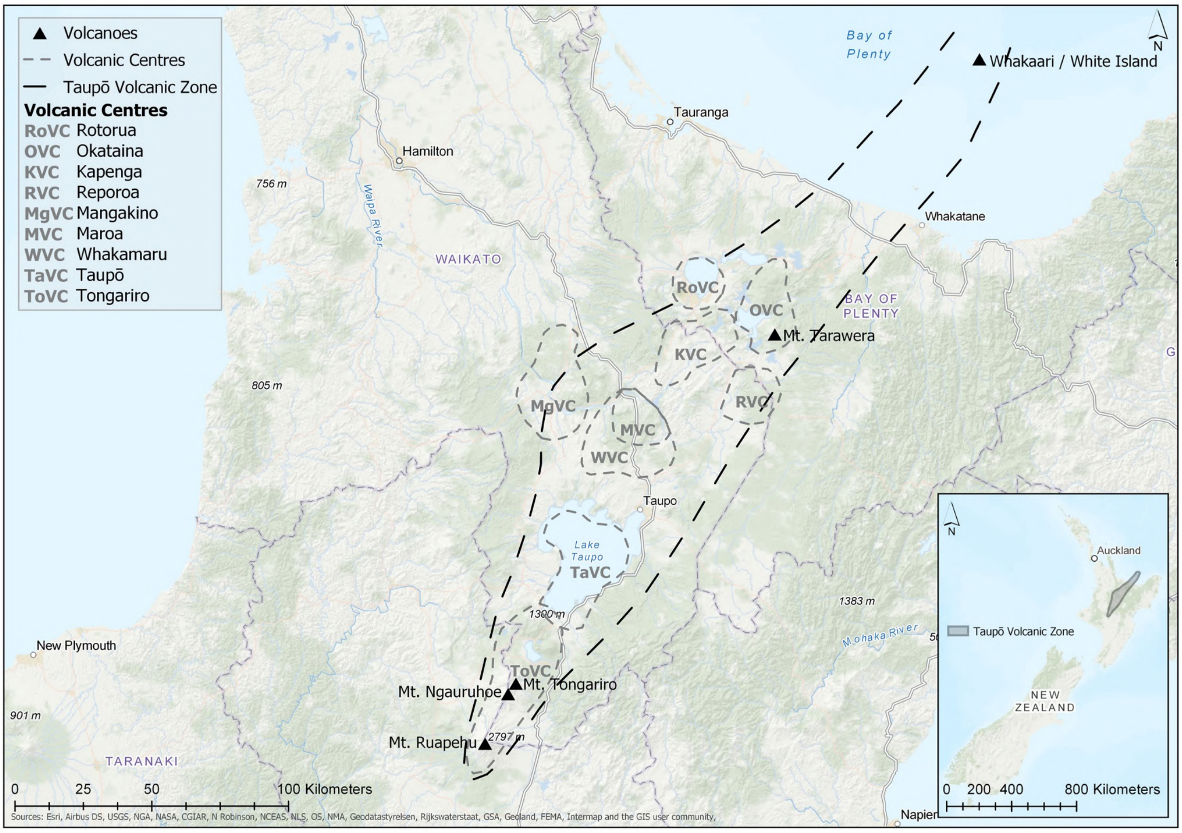

Figure 1.5: The Taupō Volcanic Zone in A-NZ's central North Island.

This central section hosts eight caldera volcanoes (*Figure 1.5*) and is the world's most active caldera system, with at least 28 major eruptions from the central TVZ in the last 26,000 years (*Table 1.1*; Froggatt, 1997). Two of these caldera volcanoes are of particular interest; the Taupō Volcanic Centre (TaVC), which is one of the world's most frequently active calderas and home of the world's youngest super-eruption (the Oruanui eruption 26,000 years ago), and the Okataina Volcanic Centre (OVC), in which the most recent central TVZ eruption, the 1886 Tarawera eruption, occurred (Nairn, 1993; Froggatt, 1997; Wilson, 2001; GNS Science, 2010b).

Volcanism has had the greatest impact on the North Island's landscape and environments during the last 1.6 million years through a range of complex and diverse volcanic events (Wilson, Houghton & Scott, 1995). Historical and geological records (*Table 1.1*) indicate that the central TVZ experiences unrest every few decades and erupts every few hundred years. These eruption events can be violent, similar to other rhyolitic (high-silica content magma) volcanoes, such as Chaitén in Chile and Rabaul caldera in Papua New Guinea, with the Taupō Volcanic Centre (TaVC) having erupted over 35km^3 of volcanic material over its recent lifetime (Potter et al., 2015ab).

Table 1.1: TVZ volcanoes' activity history and significant eruptions (Froggatt, 1997; GNS Science, 2010b; Nairn, 1993).

VOLCANO	SIGNIFICANT ERUPTIONS (YEAR)	OVERALL ACTIVITY
Mt. Ruapehu	1895, 1995, 1995-1996	Started erupting 250,000 years ago 60+ minor eruptions since 1945
Tongariro Volcanic Centre		Consists of 12 vents, formed over 275,000 years
Mt. Nguaruhoe	1954, 1973, 1974, 1975	Youngest, most active cone if the TVC 60 eruptions since 1839
Mt. Tongariro	Te Maari crater – 2012	The Red and Te Maari craters were active in the 1800s
Taupō	Oruanui eruption – 27,000 years ago 'Taupō Eruption' – 1,800 years ago (232 AD)	Began erupting 300,000 years ago 26 eruptions between Oruanui and Taupō eruptions
Okataina Volcanic Centre		
Mt. Tarawera	18,000, 15,000, 11,000, 800 years ago	Rhyolitic eruption 18,000 years ago built up the current Mt. Tarawera formation
Tarawera/Rotomahana	1886	Eruption marked a dramatic change in the style of the volcano from rhyolitic to basalt scoria

Haroharo	7,500, 5,000 years ago	Rhyolite composition
Haroharo/Okareka	21,000 years ago	Rhyolite composition
Haroharo/Rotoma	9,000 years ago	Rhyolite composition
Rotokawau	3,500 years ago	Basalt composition
Okareka	13,500 years ago	Rhyolite composition
Whakaari (White Island)	1975-2001 2019	Frequent small eruptions

Notable events from the central TVZ are the Oruanui eruption 26,000 years ago, the "Taupō Eruption" 1,800 years ago, the Kaharoa eruption in 1314 AD, and the Tarawera eruption in 1886. The Oruanui eruption, from the TaVC, was so significant that almost all of A-NZ experienced ash fall and the "Taupō Eruption", also from the TaVC, caused widespread impacts with areas near Lake Taupō buried in more than 100m of pyroclastic flow deposits (Froggatt, 1997). The 1314 AD Kaharoa eruption, from the Okataina caldera (OVC), was the largest eruption to have occurred in A-NZ in the last 1000 years, ejecting ash that covered much of the northern North Island, with an eruption of its size today likely having widespread and long-term impacts on A-NZ's environment, infrastructure, industries and economic activity (Johnston et al., 2000; Johnston, Nairn & Martin, 2002). The 1886 Mt. Tarawera eruption, also from the OVC, devastated the surrounding region with significant surges and ash fall and resulted in the deaths of more than 100 people (Nairn, 1993). These prominent events from the central TVZ demonstrate the potential complexity, diversity and magnitude of impacts that A-NZ populations could experience in the future.

The hazards generated by these events from caldera volcanoes, such as pyroclastic flows and ash fall, can cause widespread impacts across the North Island, and, in the case of larger eruptions (VEI 5 and above; *Table 1.2*), may also affect the South Island. These volcanic impacts have the potential to disrupt and/or severely damage the built, social, cultural and economic environments (Scott, Houghton & Wilson, 1995; Potter et al., 2015b).

Table 1.2: The Volcano Explosivity Index (VEI) is a numeric scale that measures the relative explosivity of eruptions. It is derived from characteristics of eruptions such as volume of products ejected and eruption column height and ranges from VEI 0 to VEI 8. The scale is logarithmic, with each interval representing a tenfold increase in observed ejecta criteria, with the exception between VEI 0, VEI 1 and VEI 2 (United States Geological Survey (USGS), 2017).

The VEI values within this table were derived from Newhall & Self, 1982; Wilson, 2001; USGS, 2015; Bennet, Hampton & Hikuroa, 2016; and Global Volcanism Program (GVP), 2019.

VEI	VOLUME OF EJECTA	CLASSIFICATION	ERUPTIONS
0	**$<10^4 m^3$**	Hawaiian	Mt. St. Helens, *2004*
1	**10^4-$10^6 m^3$**	Hawaiian/Strombolian	Mt. Ruapehu, *2007*
2	**10^6-$10^7 m^3$**	Strombolian/Vulcanian	Whakaari (White Island), *2001*
3	**10^7-$10^8 m^3$**	Vulcanian	Mt. Ruapehu, *1995-96*
4	**10^8-$10^9 m^3$**	Vulcanian/Plinian	Mt. Pelée, *1902-05* Eyjafjallajökull, *2010* Calbuco, *2015*
5	**10^9-$10^{10} m^3$**	Plinian/Ultraplinian	Kaharoa, *1314 AD* Tarawera, *1886* Mt. St. Helens, *1980* Cordon-Caulle, *2011*
6	**10^{10}-$10^{11} m^3$**	Plinian/Ultraplinian	'Taupō Eruption', *1,800 years ago* Mt. Pinatubo, *1991*
7	**10^{11}-$10^{12} m^3$**	Plinian/Ultraplinian	Mt. Tambora, *1812*
8	**$>10^{12} m^3$**	Plinian/Ultraplinian	Oruanui Eruption, *27,000 years ago* Yellowstone Mesa Falls, *1.3 million years ago*

These impacts can be the result of direct primary and secondary hazards (*Table 1.3*), such as, pyroclastic flows (primary hazard), which are hot, gaseous clouds that are laterally transported away from the vent source at speeds up to hundreds of metres per second. Pyroclastic flows are difficult to survive, especially without severe injuries, and will most likely severely damage, if not destroy, infrastructure and buildings in their path (Johnston & Houghton, 1995). Lahars are both a primary and secondary hazard as they can occur both during and decades after the eruption itself has ceased. This prolonged occurrence is a result of lahars' ability to be triggered by excess rainfall or lake-burst water mixing with loose deposited volcanic material (McSaveney et al., 2006; Manville, Hodgson & Nairn, 2007). Lahars can also change the physical landscape through the blocking of pre-established waterways. This occurred after the "Taupō Eruption", where valleys and depressions in the Waikato River system were filled with up to 70m of pyroclastic material, which blocked the Lake Taupō outlet into the Waikato River, resulting in the outlet breaching due to subsequent refilling of the lake. This triggered the release of 20km^3 of floodwater down the Waikato River, which would affect several communities in today's landscape (Manville, 2002). Impacts can also be indirectly associated with the volcano, for example, ash fall can directly affect critical infrastructure (electricity, water, transport etc.) and, thereby indirectly affect the functionality of those critical infrastructure providers and users. This has the potential to severely disrupt society through losses in power generation and supply, damage to water systems, loss of transport, and mechanical damage, amongst other potential impacts (Johnston & Houghton, 1995). These impacts can also be linked to unrest factors, where socioeconomic issues, such as population anxiety, general unease, or decreases in tourism, can indirectly impact residents, businesses, and sometimes even national economic environments.

Table 1.3: Types of hazards presented by the Taupō Volcanic Zone volcanoes, their potential threats to life and property, and spatial extents (adapted from Scott, Houghton & Wilson, 1995).

HAZARD	THREAT TO LIFE	THREAT TO PROPERTY	AREAS AFFECTED
Acid Rain	Low	Moderate	Local to regional
Ballistics	High	High	Near vent/Local
Ground deformation	Low	Variable, dependent on location	Local
Lava flows	Low	Extremely high	Local
Lahars	Moderate	High	Local to regional
Mass Movement (e.g. debris avalanche)	Extremely High	Extremely High	Local
Pyroclastic flows	Extremely high	Extremely high	Local to regional
Seismic shaking	Low	Variable, dependent on intensity of shaking	Local
Tephra (ash and pumice) fall	Generally low, except close to vent	Variable, dependant on thickness of deposit	Local to regional
Volcanic gases	Low	Moderate	Local to regional

1.5 Risk from Silicic Volcanism

This section starts by outlining how volcanic risk is quantified, followed by an explanation of how disaster risk is managed both globally and within A-NZ (*Section 1.5.1*). This is further refined through a closer look at *volcanic* risk management globally and in A-NZ, including how this risk has been characterised by organisations within A-NZ's volcanic risk management space (*Section 1.5.2*). This section addresses parts of Objectives One and Two.

Risk is a function of hazard, exposure, and vulnerability (*Figure 1.6*). The hazard refers to the likelihood and intensity of a potentially destructive natural event, the exposure refers to the location, attributes, and value of assets and populations that are exposed to the hazard, and the vulnerability refers to the potential extent to which the assets and populations may become damaged or disrupted when exposed to the hazard event. Risk evolves spatially and temporally in response to changes in the hazard, exposure, and/or vulnerability and the interactions between these elements (Global Facility for Disaster Reduction and Recovery (GFDRR), 2016).

Figure 1.6: Risk equation (GFDRR, 2016).

International experience from other large silicic events demonstrates that unrest and/or eruptions from caldera volcanoes are a credible risk. These events can be complex involving multiple hazards, spanning over large areas, for prolonged periods of time. Understanding the potential consequences is an essential part of managing the risk associated with these events, particularly across a range of diverse environments (*Figure 1.2*) (UNDRR, 2015).

1.5.1 Disaster Risk Management

The latter part of the 20th Century saw a change in the global perception of disasters from "inevitable" to "manageable" through the implementation of preparedness and reduction measures as part of a new "comprehensive" emergency management approach to natural hazards (MCDEM, 2018). As a result, in the 21st Century, both the developed and developing worlds have made considerable progress towards the development and improvement of disaster risk management (Nirupama, 2016).

Disaster risk management (DRM), as defined by the United Nations Office for Disaster Risk Reduction (UNDRR), is "*the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to strengthening of resilience and reduction of disaster losses*" (2017) and at a global scale, is guided by the UNDRR's Sendai Framework (2015). The Sendai Framework recognises that the State has the primary role to reduce disaster risk, but that responsibility should be shared with other stakeholders including local government, the private sector, and indigenous communities (UNDRR, 2020). This perception change in disaster risk management is not only reflected in the Sendai Framework, but also in the change of risk planning methods, with a transition from "top-down" methods (closed systems where one agency identifies the problem, collects data, undertakes analysis, and implements one chosen output without wider consultation) to collaborative methods. These invite the consultation of diverse stakeholder groups and have seen a more reliable and transparent process develop (Ansell & Gash, 2008; Lane, 2005; Twigg, 2004). Collaborative disaster risk management allows stakeholders to have a better understanding of each other's values, perspectives, and needs prior to an event, reducing the potential disaster impacts and increasing the overall resilience. Furthermore, bridging across these traditional scientific boundaries allows for improved communication and trust between stakeholders, which effective disaster risk management relies on, and allows for a better framing of decision-making contexts (Gottsmann, Komorowski & Barclay, 2017; Leonard et al., 2014; Potter, Scott & Jolly, 2012).

1.5.1.1 Disaster Risk Management in Aotearoa-New Zealand

In recent decades A-NZ has experienced significant natural events, such as the Mt. Ruapehu eruption in 1995-96 and the Christchurch Earthquake Sequence (CES) in 2010-11 (Wilson et al., 2014; Woods et al., 2017). As a result, disaster risk management in A-NZ has evolved significantly (MCDEM, 2018). In A-NZ, disaster risk management is underpinned by a legislative framework including the Resource Management Act (RMA) (1991), the Building Act (2004), and the Civil Defence Emergency Management Act (CDEM Act) (2002). Regional and local level government have a further responsibility to identify and rank potential hazards (*Table 1.4*) and develop response plans around these (Potter, Scott & Jolly, 2012). The complex nature of natural hazards requires a disaster risk management method (see *Section 1.6*) that can collate and organise knowledge in an effective, transparent manner (Ritchey, 2006). The legislation aims to achieve this by promoting the sustainable management of impacts from natural hazards through collaborative efforts amongst a wide range of agencies involved in A-NZ disaster risk management, prior to an event.

Table 1.4: Volcanic hazard ranking by the Bay of Plenty and Waikato Regional CDEM Groups in their respective group plans. These hazard rankings are based on the combined likelihood and perceived consequence of each hazard (Bay of Plenty CDEM (BoP CDEM), 2018; Waikato CDEM; 2016).

VOLCANIC HAZARD	REGIONAL CDEM GROUPS HAZARD RANKING	
	BAY OF PLENTY	WAIKATO
Ash fall only	-	Very High
Caldera unrest only	High	Very High
Caldera eruption	-	High
Eruption	-	Very High
Local Source	High	-
Distal Source	High	-

1.5.2 Volcanic Risk Management

Global volcanic disasters in 1902 resulted in the establishment of volcano observatories and emphasised the importance of volcanology as a multidisciplinary science, while disasters since 1980 have enhanced the public awareness surrounding volcanoes and their hazards (Tilling & Lipman, 1993). In A-NZ, the Mt. Ruapehu 1995-96 eruption provided valuable experience in the communication and dissemination of information between science agencies and emergency management agencies. For example, of the 30 response agencies involved in the event, only one had formally approached GNS Science (the national volcano science institute) to discuss their specific information needs, indicating that there was a need for more systematic links between scientists and emergency management agencies (Ronan et al., 2000).

Experiences from recent eruptions have emphasised the multi-hazard, multi-scale and trans-boundary nature of volcanic hazards, such as the Icelandic Eyjafjallajökull eruption in 2010. This event illustrated that disasters and their impacts are not restricted within regional or district boundaries or national borders, as the eruption’s source resided in Iceland, but its ash fall related impacts were felt across Iceland, the United Kingdom, and other countries whose airlines flew in and around the British airspace (Tweed, 2012; Bird & Gísladóttir, 2012). This eruption demonstrated the unprecedented vulnerability of modern infrastructure to volcanic hazards, with the aviation industry experiencing US$2.5 billion in losses as a result of the eruption (Gottsmann, Komorowski & Barclay, 2017). Bird and Gísladóttir (2012) found that the Eyjafjallajökull eruption also identified that disaster management plans often focus on the immediate response to preserve life, but lack development in dealing with an ongoing crisis or strategies to preserve livelihoods, as Icelandic residents became frustrated and anxious about the prolonged inability to return to their homes, schools or workplaces. This is an important volcanic risk management gap to acknowledge as caldera unrest can continue for decades before eruption (such as what was experienced at Rabaul caldera), and having the ability to adapt, change, and function within such a dynamic environment is critical for effective response to caldera events.

Modern volcanic impact management has shifted from a purely geological focus (such as eruption size), to a more holistic approach, incorporating factors such as the proximity or density of nearby populations and even the pre-event response structures and plans already in place (Tilling & Lipman, 1993). This is because monitoring data or eruption forecasts alone will not reduce volcanic impacts unless they can be communicated effectively to, and acted upon by, emergency management authorities (as taught by the 1985 eruption at Nevado del Ruiz in Colombia; Voight, 1990). Therefore, effective communication between scientists, government, officials, news media and affected populations must be established prior to an event and is essential for providing an integrated response to an event (Tilling & Lipman, 1993; Ronan et al., 2000). Building these relationships and communication pathways prior to an event is also necessary due to the inherent diversity and complexity of the hazards, potential consequences, and agency information needs, as well as the geographical and temporal changes that can occur within hazards (Ronan et al., 2000).

Often, retrospective accounts of volcanic events advocate that some kind of co-operative partnership between scientists and authorities is necessary to ensure that relevant information is presented in meaningful and timely ways and is acted upon appropriately (Barclay et al., 2008). But it is not just other volcanic events that have taught important lessons about disaster risk management. The magnitude 7.8 Kaikōura earthquake that occurred in A-NZ in 2016 emphasised the importance of having a clear structure for how science research and civil defence emergency management response and recovery decision-making can be integrated, particularly for events which may require a large co-ordinated response from stakeholders (GeoNet, 2016; Woods et al., 2017). Research has also found that hazard mitigation processes or products that included stakeholder engagement in their development were more effective at communicating risk information to communities (Barclay et al., 2008).

1.5.2.1 Volcanic Risk Management in Aotearoa-New Zealand

When compared to other hazards, such as extreme weather events, flood and earthquakes, volcanic impact and risk assessments are comparatively poorly developed, especially for caldera volcanoes. This can be partially attributed to few and infrequent, damaging volcanic events occurring in A-NZ over the past few decades, causing these events to be perceived as "exotic" (Wilson et al., 2014; Gottsmann, Komorowski & Barclay, 2017). Furthermore, for most individuals, threats presented by volcanic events are relatively rare and can be tolerated in return for the many benefits of living near these caldera volcanoes (Marzocchi, Newhall & Woo, 2012).

This underdevelopment can also be attributed to the inherently complex nature of volcanic events as volcanic activity is highly variable, with events ranging from unrest that presents no immediate eruption to violent explosive eruptions that are locally catastrophic and can have effects on the global climate (Stirling et al., 2017; Barclay et al., 2008). This becomes more complex as one single event can lead to multiple cascading and compounding hazards that can last for significant periods of time (Rabaul caldera, Papua New Guinea, experienced unrest for decades before an eruption occurred; Potter, Scott & Jolly, 2012) and affect vast areas. Methods that better deal with this multi-hazard risk context are more likely to help emergency managers and communities at risk to better understand and cope with the uncertainty of caldera volcanoes (Gottsmann, Komorowski & Barclay, 2017).

Large volcanic eruptions tend to be low probability but high consequence geohazards with the potential to cause national to global-scale disasters. A large caldera event from the TVZ has been identified by the Department of Prime Minister and Cabinet (DPMC) as a low likelihood, high consequence risk for A-NZ (Security and Intelligence Group (SIG), 2011; 2016). This can be seen on the risk plot below (*Figure 1.7*) that provides a visual comparison of the approximate scale of the main components of significant risks within A-NZ and, therefore, the types of contingencies that feature in A-NZ's national and regional planning (SIG, 2011).

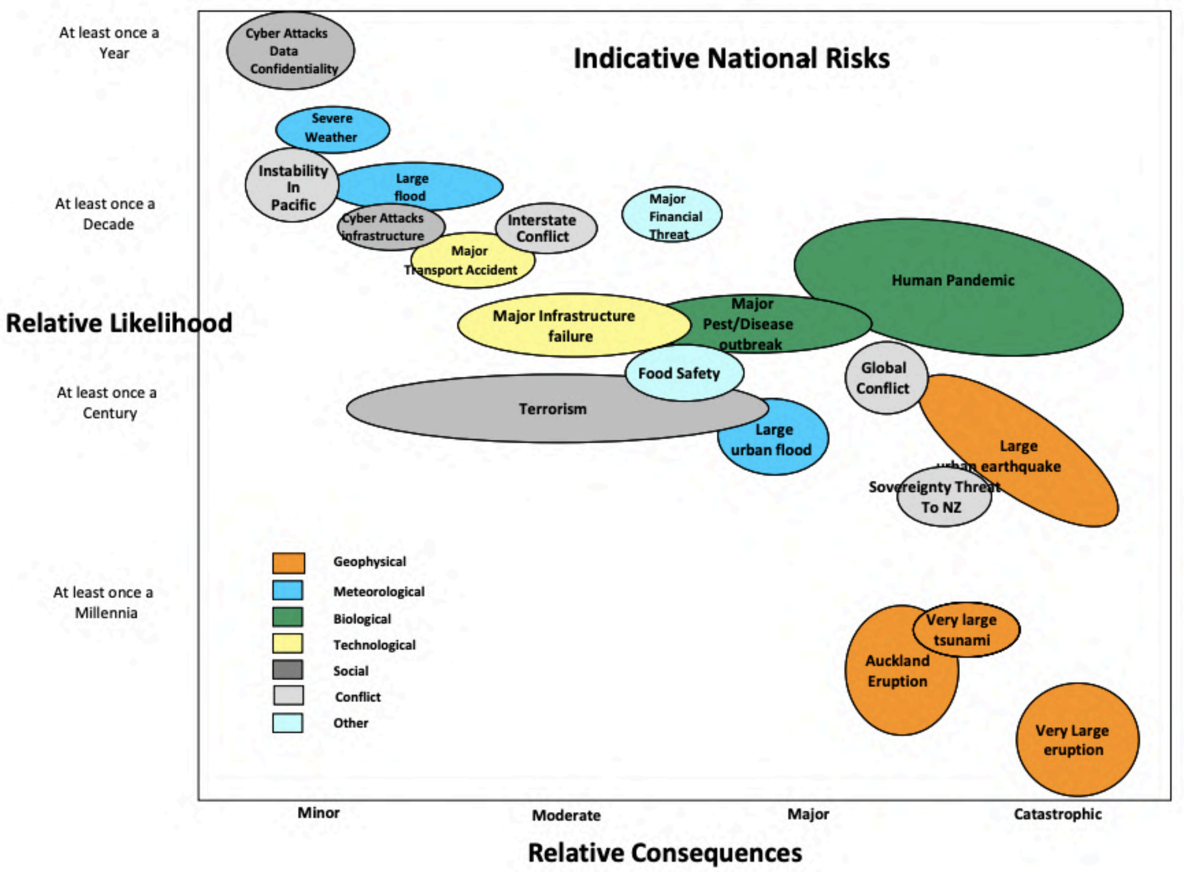

Figure 1.7: A-NZ's Indicative National Risks determined by the Department of Prime Minister and Cabinet (DPMC) (SIG, 2011).

The importance of understanding and preparing for volcanic events from New Zealand's caldera volcanoes is emphasised by the specific characteristics of these events, particularly in comparison to other hazards. Volcanic events present a wide range of initial events to begin with. Then, from each of these individual events, the paths can evolve into a vast range of outcomes, each with its own range of threats to life and property and its own related uncertainty as to what specific set of outcomes eventually occurs. The dynamic complexity of potential volcanic hazards and the significant exposure of populations and assets in the central North Island mean that a comprehensive risk management strategy is required to mitigate future volcanic events.

Caldera volcanoes also present a difficult challenge as potential super-volcanic eruptions from caldera centres are often the focus of significant public and media interest. In addition, eruptions associated with calderas are often misunderstood as always generating catastrophic disasters, which is not actually the case (NZIER, 2009; Potter, Scott & Jolly, 2012). Rather, caldera volcanoes can often experience unrest activity, with no immediate eruption, and while these events do not present immediate eruptive hazards, they do present very real risks of their own (Gottsmann, Komorowski & Barclay, 2017). Unrest episodes can include several hazards, such as landslides, triggered by significant earthquake shaking, or flooding, triggered by ground deformation activity. The perception that unrest will always lead to immediate and catastrophic eruption causes significant anxiety amongst the public and, combined with the inherent uncertainty of these potentially long-lived, non-eruptive events, can have profound impacts on event management (Barclay et al., 2008; Gottsmann, Komorowski & Barclay, 2017). It is also important to emphasise to those unfamiliar that while these events can manifest in super-eruptions, smaller-scale eruptions (VEI 4 and below) are far more likely to occur, and unrest episodes, resulting in no eruption, are even more likely.

Management of these complex small eruption or unrest episode events, with its inevitable uncertainty in terms of potential outcomes, creates major challenges for scientists, authorities, the public and the media (Gottsmann, Komorowski & Barclay, 2017). Therefore, the capacity to identify the issues of and solutions for potential volcanic crises relies on dialogue and collaboration between scientists, emergency managers and those at risk, and can be built from a framework that can collate and organise knowledge and practical experience from a wide range of disciplines (Fearnley & Beaven, 2017). This is particularly important because potential future volcanic risk management strategies are adopted by these stakeholders, and used to develop organisational strategies and improve preparedness, in the context of uncertain futures (Keough & Shanahan, 2008; BoP CDEM, 2018; Waikato CDEM, 2016). This, therefore, requires this knowledge to be easily accessible and understood by all stakeholders and end-users; ideally it should be produced within a modular, sustainable framework that can be updated as the science and policy that drives volcanic risk management evolves (Ritchey, 2006). This framework would need to acknowledge that different groups involved in volcanic risk management will use science information to meet distinct and different needs (Johnston et al., 2000).

1.6 Scenarios and Scenario Frameworks

This section of *Chapter 1* provides a literature review/context on scenarios (*Section 1.6.1*) and scenario frameworks (*Section 1.6.2*), outlining what they are, how they work, what their benefits are, and what their limitations are. This section addresses part of Objective Two. The potential methods of development for scenarios and scenario frameworks are outlined in *Chapter 2*.

1.6.1 Scenarios as a tool for Disaster Risk Management

Scenarios are prospective stories about how future volcanic events may evolve, including their impacts on surrounding environments (Bowman et al., 2013). They are a credible, detailed, process-focused decision-making tool that is a part of A-NZ's disaster risk management toolbox for future strategic planning (Keough & Shanahan, 2008). These scenarios typically bring together many complex parts into coherent stories and are an effective platform for integrating knowledge from various diverse disaster risk management domains, allowing this integration throughout all stages of development, nurturing more useful and useable products for all relevant stakeholders (Boaz & Hayden, 2002; Tonini, Sandri & Thompson, 2015; Doyle et al., 2018; Loughlin et al., 2015).

Volcanic event scenarios have proven useful for several purposes within volcanic risk management; such as evaluating impacts and mitigation measures on environments, comparing volcanic hazards, identifying weaknesses in pre-established exercises and preparedness applications, and as decision support tools for authorities and communities (Johnston et al., 2000; Zuccaro et al., 2013; Biass et al., 2016ab; Reichardt, Ulfarsson, Pétursdóttir, 2019; Deligne et al., 2017ab; Hayes et al., 2018). These scenarios are a tool that can be used through all stages of volcanic risk management – pre-event preparedness, crisis response, and recovery stages – and have been identified as an under-utilised resource for disaster risk management planning and communication (Jolly & de la Cruz, 2015; Oven et al., 2016). Scenarios have proven to be beneficial amongst other studies, where research has shown that they enabled new understanding to stakeholders around volcanic risk, challenged existing assumptions, and identified new research opportunities (Reichardt, Ulfarsson, Pétursdóttir, 2019; Ramirez et al., 2015). They are particularly beneficial in a volcanic hazards and impacts context as they allow "what-if" ideas to move to the forefront of pre-event/"peace-time" discussions and research, which reflects the focus during events/crises where "what if xyz occurs…?" would be the leading question to scientists and emergency management authorities (Ravetz, 1997).

Traditionally, scenarios of volcanic unrest and/or eruption events are based on data and information on the frequency and severity of previous episodes of activity and computer modelling of the range of individual hazards produced by the volcano (Jolly & de la Cruz, 2015). These scenarios can be developed to include several aspects of the hazards and impacts that could potentially occur and can be defined in terms of magnitude, location, timing, style of potential eruption, area affected, and the probability of occurrence (Potter, Scott & Jolly, 2012; Reichardt, Ulfarsson, Pétursdóttir, 2019). By using historic and analogue data from local and international caldera volcanoes, possible future scenarios can be developed and communicated (Potter et al., 2015b).

Scenario development benefits disaster risk management as it recognises the inherent weakness in more common tools such as forecasts, which are single-outcome methods focused on predicting the future, where scenarios focus on attempting to understand how uncertainties in organisational environments might interact in unexpected ways and therefore alter the future (Bowman et al., 2013). Scenarios allow development of multiple stories of possible different futures to demonstrate the underlying, unpredictable, unstable and uncertain nature of the future in order to communicate and characterise uncertainty to decision-makers (Moats, Chermack & Dooley, 2008; Kwakkel, Auping & Pruyt, 2013).

Volcanic event scenarios can help stakeholders to logically think and step through the components of any hazard, impact or risk assessment. They can work in a similar style to event-trees but avoid the numerical probability aspect of event-trees, which can often over-complicate the information presented and not hold much meaning to those who do not directly understand the statistics. This process of working through a scenario can help to improve understanding of the effects of unrest and/or eruptive activity on the vulnerabilities of affected populations (Gottsmann, Komorowski & Barclay, 2017). This also makes it easier to follow how one hazard or impact occurs alongside or as a result of another. This same process is a useful tool for conveying hazard and impact information among various diverse stakeholder groups, such as scientists, emergency managers, and communities (Newhall & Hoblitt, 2002).

Scenarios, however, have their limitations, primarily that they differ from reality and are not a definitive prediction of actual future circumstances, as only one or a few scenarios, out of an infinite number of potential scenarios, is considered. This limitation could be labelled as misleading, particularly for stakeholders not from a research science background, however, Bloom and Menefee (1994) and Davies et al. (2015) argue that scenarios can act as a starting point for initial awareness. This starting point can improve understanding of the wide range of possibilities presented by one volcano and that, as long as stakeholders involved are aware that the small number of scenarios presented does not cover all potential hazard variations and impacts, scenarios are still useful and useable. The research presented here emphasises this point, as it focuses on the scenario development, rather than the product itself and, by doing so, allows collaborators to understand the complexity of caldera risk and the broad and varied potential outcomes that can occur from these events. Therefore, even if stakeholders only choose to develop one scenario path, they are already aware of the limitations. Furthermore, by demonstrating that each scenario is only one path of many, these scenarios can address the inherent uncertainty of volcanic systems and can work as a useful tool for understanding and communicating what may happen in the face of these complex environments (Marzocchi, Sandri & Selva, 2010).

Another limitation with scenario approaches is that researchers commonly have to attempt to capture the full breadth of uncertainty about the future into a small set of scenarios, restricting what uncertainty is actually presented within a suite of scenarios (Kwakkel, Auping & Pruyt, 2013). To accommodate this challenge, the research here attempts to develop a modular, adaptable scenario framework; the ECLIPSE Scenario Framework (*Chapter 3*).

1.6.2 Scenario Frameworks

Currently, scenario planning literature provides models of scenario building, however, it lacks guidance and generally does not provide stakeholders with the information they need to properly undertake scenario planning onn their own accord (Keough & Shanahan, 2008). This lack of guidance and information stems from a broader disaster risk management gap where guidelines between those that provide and those that receive scientific advice are absent (Gottsmann, Komorowski & Barclay, 2017). To amplify this, the diverse and variable drivers of, and constraints on, the use of science and policy by different stakeholders further makes it difficult to provide one-size-fits-all management tools and recommendations (Oven et al., 2016). The ECLIPSE Scenario Framework developed within this research aims to acknowledge and cater to these various and diverse needs and applications while also attempting to make it easier to understand what may happen in the face of complex caldera environments and open dialogue around the management of calderas (Marzocchi, Sandri & Selva, 2010).

As volcanic events, particularly from caldera volcanoes, involve multiple cascading and compounding hazards and impacts, caldera risk management is a complex issue that requires an interdisciplinary approach, incorporating knowledge and practical experience, towards its management. The framework tool developed therefore, must provide the appropriate level of detail to inform decision-making, should be derived from a common source, and should also consider different hazards and impacts from caldera volcanoes simultaneously in both space and time dimensions (Stirling et al., 2017; Barclay et al., 2008). This disaster risk management tool should also address the socio-economic causes and consequences of exposure to volcanic events, rather than focusing only on the hazards themselves, in order to achieve effective volcanic risk communication (Barclay et al., 2008). As different stakeholders often focus on different aspects of the overall risk presented by caldera volcanoes, the framework must provide a flexible, knowledgeable, and collaborative regime that is able to adapt to rapid changes in the risk environment (Cash et al., 2003; Barclay et al., 2008).

The collaborative development approach (*Chapter 2*) of the ECLIPSE Scenario Framework (*Chapter 3*) follows these recommendations; it accommodates two-way communication between stakeholders where enough information is provided for decision-makers to judge whether or not they need more, rather than overwhelming them with too much, and possibly unnecessary, information (Doyle et al., 2018). By using the collaborative approach, and providing transparency throughout, stakeholders are also able to see how and why certain outcomes develop (Doyle & Paton, 2017). The framework also helps to combine the most important aspects of scientific information and the understanding of the context in which emergency management actions must be made (Gottsmann, Komorowski & Barclay, 2017). Furthermore, once a comprehensive scenario planning process, such as the ECLIPSE Scenario Framework, has been outlined, researchers and stakeholders alike are enabled to explore specific aspects of the overall framework, which ultimately helps stakeholders make better and more informed decisions (Keough & Shanahan, 2008). This is also beneficial as the exploration by end-users can potentially identify possible impacts that were previously not considered or identify research gaps within the science – where the development of science into a framework itself creates a further demand for more science information; the "demonstration effect" (Oven et al., 2016).

1.6.3 Previous and Aligned Scenario Research

The research developed here also builds from aligned research from other natural hazard scenarios, such as the Alpine Fault Magnitude 8 (AF8) project (Orchiston et al., 2016) and the Determining Volcanic Risk in Auckland (DEVORA) AVF scenario suite (Hayes et al., 2018). The AF8 scenario follows a maximum credible hazard event and impact scenarios for a future $M_w8.0$ Alpine Fault earthquake across A-NZ's South Island, while the DEVORA research developed a suite of eight scenarios that represent the credible range of potential future AVF eruptions that can be used to inform volcanic impact and risk studies.

This research also builds from previous scenario work undertaken by the Caldera Advisory Group (CAG), which details a caldera unrest scenario, developed in three stages (Waikato Regional Council (WRC), 2012).

2 RESEARCH METHODOLOGY

Globally, there is no standardised level of appropriate information between those who provide and those who receive scientific advice (Gottsmann, Komorowski & Barclay, 2016). However, current best practice has seen an increasing emphasis on open dialogue methodologies, rather than "policing" divides between domains and their information needs. This new practice has seen consistent communication and trust building become key to ensuring that processes and products are legitimate, useful, and useable (Fearnley & Beaven, 2017; Barclay et al., 2008). Current volcanic risk management initiatives further emphasise that it is in the best interests of research science to understand and work with policy-makers and the community so that research is designed to be useable, useful and used within policy and community strategy development (Boaz & Hayden, 2002). This is particularly important as the volcanic event decision-making process specifically requires comprehensive multi-disciplinary collaborative approaches to management and requires experts across a diverse range of fields (Marzocchi, Newhall & Woo, 2012; Stirling et al., 2017).

This chapter outlines part of the literature review that was carried out to inform the methods used throughout the research project. This chapter partially addresses Objective Two; to develop methods for disaster hazard and impact scenario development for silicic volcanism. This chapter begins with a review of traditional disaster risk management approaches and their limitations (*Section 2.1*), followed by a description of the conceptual disaster risk management framework used to help frame and guide this research (*Section 2.2*), and finishing with an in-depth explanation of the methodological approach followed for the development of the ECLIPSE Scenario Framework and ECLIPSE Scenarios (*Section 2.3*).

2.1 TRADITIONAL DISASTER RISK MANAGEMENT APPROACHES

Disasters are the serious disruption of the functioning of a community or society at any scale due to hazardous events interacting with exposed populations and/or assets and the vulnerability of those exposed populations/assets, leading to human, material, economic, and/or environmental losses and impacts (UNDRR, 2018). Society, therefore, works to recognise and understand the risks and factors that could lead to or cause disasters, and in particular, potential mitigation measures that could be implemented to minimise the impacts from these events, through disaster risk management (de Guzman & Unit, 2003).

Risk management processes and practices have historically been driven by a "top-down" approach, with governments in the late 1970s beginning to institutionalise disaster risk management processes and practices. Traditionally, this management approach is hallmarked by themes of technical capacities and expertise, a hierarchical model of management where authorities have the skills, knowledge and experience that allows the management of risks, and a dependent public (Scolobig et al., 2015). This approach makes two assumptions; that the public must trust the authorities' judgement and follow their advice closely, and that risk problems (especially those related to risk mitigations, warning systems and emergency management) can be solved through technical innovation, particularly if coupled with effective economic management (Scolobig et al., 2015). However, recent disaster experience and research have emphasised that there are fundamental challenges to traditional approaches to disaster risk management, illustrated by the limited uptake of research science into disaster management and policy (Scolobig et al., 2015; Davies et al., 2015).

At a broad level, this recent experience and research has illustrated that the relationships between technical knowledge, social practices and political pressures are not as simple as the "top-down" approach presumes (Scolobig et al., 2015). This is emphasised by the common lack of communication between groups involved in the science and policy domains, which is imperative in order to achieve the implementation of science into policy applications (Davies et al., 2015). Often potential end-users do not know what science can or cannot say and therefore do not know what to ask of scientists. Similarly, scientists do not know what potential end-users need or want (Oven et al., 2016). Furthermore, the different goals of the different stakeholders involved can lead to differences in characterising the risk, which compromises effective communication and, therefore, effective risk management (Barclay et al., 2008).

Research further suggests that technology-centred, passive, one-way risk communication is poorly interpreted, often misunderstood, and can potentially decrease public trust in authorities (Scolobig et al., 2015). This poor interpretation and misunderstanding is often driven by the overemphasis on probability-based disaster risk assessment and management, which involves statistical analysis and an understanding of what those statistical probabilities mean, something non-scientists may not necessarily be familiar with. This is also a particularly tricky issue for caldera eruptions because low-probability (infrequent) events, that are also poorly-quantified or poorly understood, can be perceived as a lesser priority, however, still present significant consequences for society (Davies et al., 2015).

These issues clearly demonstrate that stakeholders who use science need to be a part of the conversation as their demands ultimately drive whether or not science is useful and actually put into practice. Therefore, by including these stakeholders, the needs for science becomes clearer and the supply of science will better match those needs. It is also important that disaster management expertise should be combined with public concerns and local knowledge through these stakeholder-led processes (Oven et al., 2016; Scolobig et al., 2015). This further indicates that contemporary disaster risk management approaches must be adaptive, iterative, and flexible and therefore it is evident that alternative strategies (to the traditional strategies) are required to enable stakeholders to prepare for poorly-quantified or uncertain events.

2.2 Conceptual Disaster Risk Management Framework

It is widely accepted that the effective use, value, and application of information across science-policy domains depends on three criteria; scientific credibility of information, its relevance to the needs of stakeholders, and the legitimacy of both the information and its development process (Fearnley & Beaven, 2017). It is therefore important that volcanic risk management is not viewed and developed in isolation but within broader contexts, such as social and economic environments, and across disciplinary boundaries (*Figure 1.2 in Chapter 1*; Barclay et al., 2008; Cash et al., 2003).

To cross disciplinary boundaries requires "boundary objects", such as scenarios, which are collaborative processes or products that are "*both adaptable to different viewpoints and robust enough to maintain identity across them*" (Cash et al., 2003, p.387). These objects require a method that can consolidate and translate information in a way which is legitimate. In order to achieve this legitimacy, the products must be both relevant, which is required within all government and community (policy) domains, and credible, which is required within the research science domain, illustrated in *Figure 2.1* (Beaven et al., 2017). These requirements from each domain can create a range of incompatible demands. Therefore, methods that include collaboration and co-production can help provide balance, compromise and inclusion towards these demands, as well as providing stakeholders with more transparent access to the development process. These collaboration processes are also more likely to produce relevant information as they engage with end-users early, defining the data needs, and allowing these wants and needs to act as anchoring nodes to drive development in legitimate directions (Cash et al., 2003; Boaz & Hayden, 2002; Tonini, Sandri & Thompson, 2015; Doyle et al., 2018). Furthermore, the increase in transparency empowers stakeholders by allowing them access to information they would otherwise not have had (Scolobig et al., 2015).

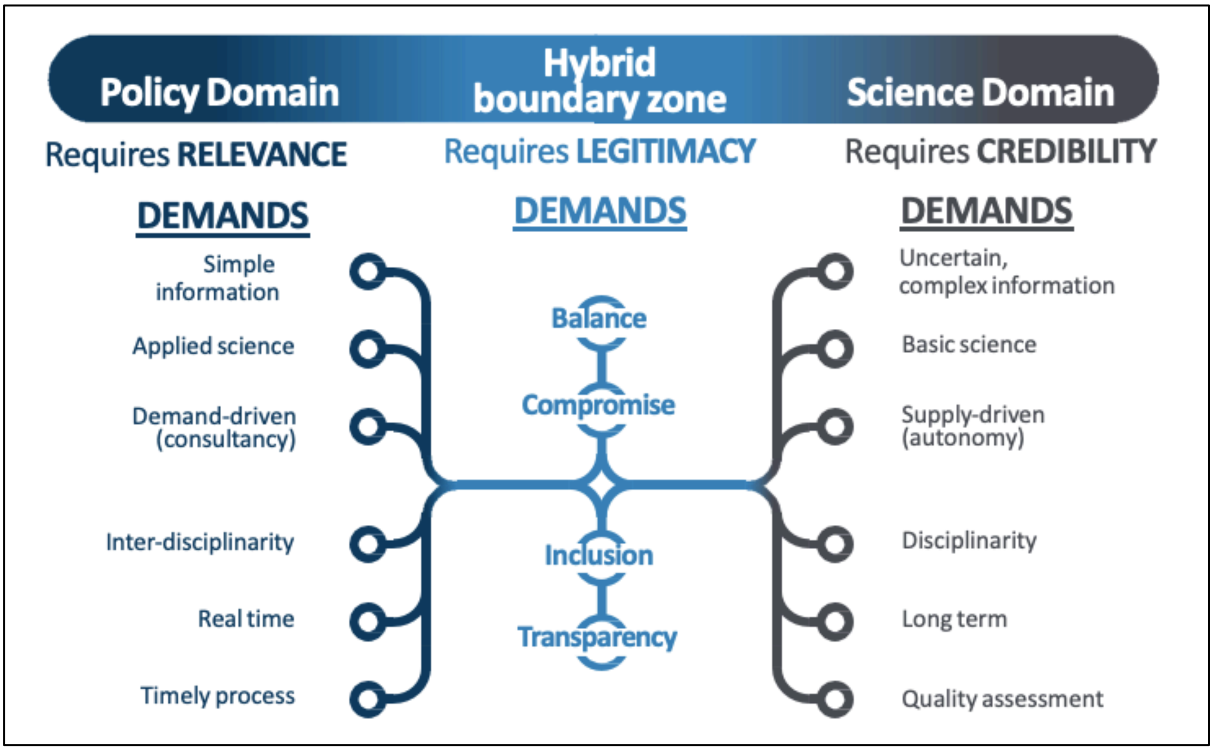

Figure 2.1: Boundaries between policy and science domains in collaborative research (Beaven et al., 2017; Cash et al., 2003; Parker & Crona, 2012; Sarkki et al., 2013).

Scenarios are an effective volcanic risk management "boundary object" that can accommodate this cross boundary information integration and allow co-production throughout all stages of development (Davies et al., 2015; Ritchey, 2006; Oven et al., 2016; Barclay et al., 2008). Scenarios, developed with awareness of the relevant contexts, can act as a useful tool for developing risk management strategies. The information that informs the scenario in the future can be developed by both scientists and potentially affected communities (through representatives, such as CDEM Groups). Together these efforts can create hazard and/or impact scenarios (Davies et al., 2015).

This co-production methodology invites two-way communication, where stakeholders are supported in understanding and acknowledging each other's wants and needs (demand and supply). The methodology also ensures that all involved understand how information is credible and relevant (Doyle & Paton, 2017; Doyle et al., 2018; Fearnley & Beaven, 2017). The outcome, whether it be the process or the final product, is likely to be better than any one group could achieve on its own or by means of only consultation (rather than involved engagement). The co-production process is therefore beneficial, not just because of mutual learning and sharing of knowledge, but because the knowledge, process, and products that result from it are more likely to be useful, useable and used across a more diverse range of applications because of the perception of their increased relevance (Davies et al., 2015).

2.3 ECLIPSE Scenario Framework Methodological Approach and Development

A specific methodology for volcanic event management must be adaptable and flexible to accommodate the complex diversity of the physical setting and the social, cultural, economic, and political environments (*Figure 1.2 in Chapter 1*). As a result, volcanic risk management must sit in a broad, dynamic framework that incorporates a wide range of approaches and stakeholders that can inform the factors that contribute to disaster risk management and address uncertainty clearly. This framework needs a clear understanding of a range of basic components of volcanic risk management, including but not limited to the range of volcanic behaviour, the uncertainties associated with changing behaviour, and the types of information needed by decision-makers to act on. This robust framework needs to be accompanied by trust and understanding between the key stakeholders involved in its development (Barclay et al., 2008; Jolly & de la Cruz, 2015; Stirling et al., 2017).

This research follows a multi-stage approach to the methodology and development of the ECLIPSE Scenario Framework and ECLIPSE Scenarios. Firstly, a review of previously developed individual scenario research and production in A-NZ and global silicic event impact case studies was undertaken (*Chapter 1*; *Appendix F*). This was coupled with a review of the hazard and impact data already established within A-NZ's disaster risk management approaches and literature (*Chapter 1*). Then, workshops and individual interviews were undertaken throughout the scenario development process with key ECLIPSE stakeholders to scope, inform, refine and evaluate the ECLIPSE Scenario Framework and ECLIPSE Scenarios and this is illustrated in *Figure 1.4* in *Chapter 1* and in *Figure 2.2*.

Key ECLIPSE stakeholders (*Table 2.1*) were previously identified within the ECLIPSE programme formation in 2017, an idea strongly supported by the CAG. Members included in the ECLIPSE programme, and thus this research, were invited to be involved as they play key roles and have key responsibilities in A-NZ volcanic disaster risk management. They are also

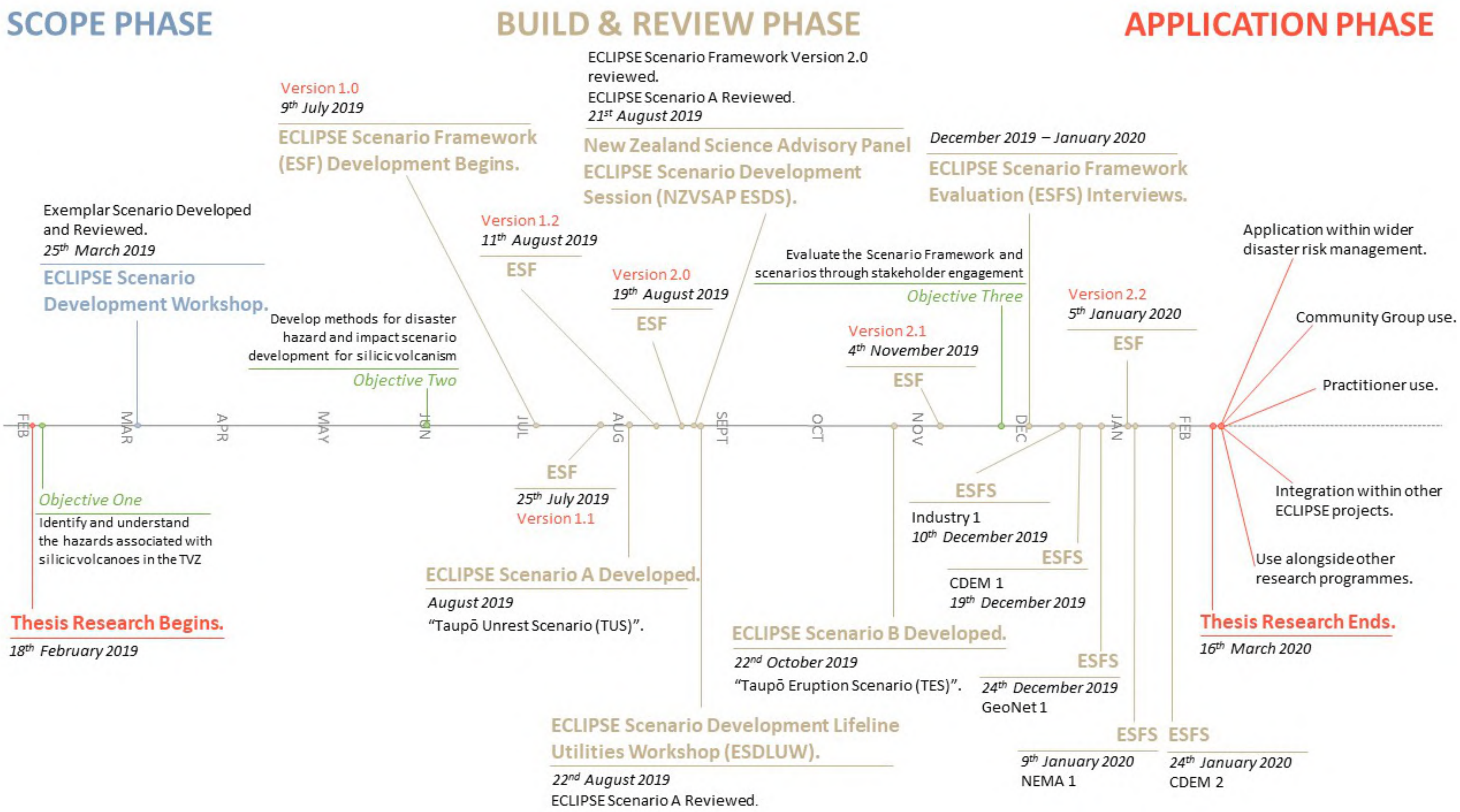

Figure 2.2: ECLIPSE Scenario Framework and ECLIPSE Scenarios development and research timeline illustrated with research objectives, major stakeholder engagement activities, and the research's beginning and completion dates.

stakeholders that have previously expressed interest in being involved with the development of preparedness and mitigation strategies for A-NZ's caldera volcanoes.

Table 2.1: List of organisations involved in the ECLIPSE stakeholder groups engaged with throughout this research. ✓ illustrates that at least one representative from the organisation, and therefore stakeholder group, listed attended one or more of the workshops or interview opportunities, while ✕ illustrates that no representatives attended.

STAKEHOLDER GROUP	ORGANISATIONS	MARCH WORKSHOP	AUGUST REVIEWS	EVALUATION INTERVIEWS
Civil Defence Emergency Management	Bay of Plenty CDEM	✓	✓	✓
	Waikato CDEM	✓	✓	✓
	NEMA (formerly MCDEM)	✕	✓	✓
GeoNet	GeoNet Volcano team	✓	✓	✓
Industry	Federated Farmers	✓	✕	✓
	Ministry for Primary Industries (MPI)	✓	✕	✕
	Rural Support Trusts	✓	✕	✕
Iwi	Ngāti Tūwharetoa	✓	✕	✕
	Te Arawa	✓	✕	✕
Lifeline Utilities	See *Appendix D* for full list	✓	✓	✕
Research Science	Massey University	✓	✓	✕
	University of Auckland	✓	✓	✕
	University of Canterbury	✓	✓	✕
	Victoria University	✓	✓	✕

Workshops are a literature-supported methodology for collecting qualitative data to inform the ECLIPSE Scenario Framework and ECLIPSE scenarios' production. Workshops, a type of deliberative and inclusive process (DIP), have been increasingly used globally as they give previously excluded groups a voice in decision-making and bring together a diverse range of stakeholders to work together. The particular benefit of using workshops comes from scientific knowledge being openly deliberated upon, and sometimes challenged, by those who are experts within the policy and decision-making domains of disaster risk management (Barclay et al., 2008; Stirling et al., 2017). Workshops are also beneficial because they foster two-way communication and provide an environment for brainstorming and developing ideas, rather than searching for the "right" answer or solution (Doyle & Paton, 2017; Doyle et al., 2018). Therefore, semi-structured workshops, broadly guiding participants in particular topics, were used throughout this research.

2.3.1 ECLIPSE Scenario Development Workshop

To start the engagement process for this research a workshop was undertaken with key ECLIPSE stakeholders on the 25th March 2019 at GNS Science, Wairakei. The aim of this workshop was to scope the wants and needs of stakeholders and end-users of A-NZ volcanic risk management to inform the scenario framework development. The ECLIPSE Scenario Development Workshop (ESDW) was also designed to communicate knowledge between stakeholders and the research team to build a shared understanding of the research. The specific objectives of the workshop were to;

- Identify how scenarios might be used by different stakeholders.
- Identify what useful and useable scenarios would look like.

The ESDW was undertaken early in the process to ensure that the potential uses and applications of the scenarios were identified and embedded into the scenarios' framework to begin with. This would help ensure that the scenarios were useful and useable for end-users from the beginning and allowed follow-up interviews/focus groups to occur throughout the development process, further expanding on requirements expressed within the ESDW.

The ESDW involved stakeholders participating in a series of three exercises (*Appendix B*). These exercises involved prompt questions posed to participants, which were developed prior to the ESDW by consultation from the research team and ECLIPSE members. Stakeholders included representatives from a diverse range of organisations involved in disaster risk management in A-NZ (*Table 2.1*). Exercises were undertaken in groups with a facilitator to record answers, prompt discussion if it stalled, and mediate if necessary.

The ESDW allowed the research team to gain a broad insight into the structures, values, and perspectives of particular emergency management organisations. The particular benefit was that participants had the ability to drive the discussion to more specific sub-topics in response to the broader prompt questions provided. This was a strength of the approach and allowed participants to emphasise issues of concern relevant to their specific discipline of practice, roles and responsibilities.

2.3.2 New Zealand Volcano Science Advisory Panel ECLIPSE Scenario Development Session

The first stage of the review process for this research involved a brainstorming session with members of the New Zealand Volcano Science Advisory Panel (NZVSAP) on 21st August 2019 at the NEMA Parliament building in Wellington. The aim of this session was to present the ECLIPSE Scenario Framework (Version 1.2; *Appendix C*) and the first ECLIPSE Scenario developed (Scenario A: Taupō Unrest Scenario; *Chapter 4*) to representatives of organisations involved in A-NZ's national level volcanic risk management.

The NZVSAP ECLIPSE Scenario Development Session (NZVSAP ESDS) involved stakeholders brainstorming ideas and participating in discussions surrounding three questions in response to the ECLIPSE Scenario Framework and ECLIPSE Scenario A. These questions were;

- Are there any gaps or issues with the current approach [to the scenario framework and/or scenario]?
- Will this [scenario framework and/or scenario] be useful for national level Civil Defence Emergency Management planning?
- How could these scenarios help with your [the participants'] science objectives?

The NZVSAP ESDS enabled the research team to identify areas of importance for national level emergency management within the ECLIPSE Scenario Framework. It allowed participants to emphasise points of interest or areas of further development, such as the ability of the framework to adapt with changing science in future and the need for guidance for use of the framework and/or scenarios.

2.3.3 ECLIPSE Scenario Development Lifeline Utilities Workshop

The second stage of the review process for this research involved a workshop with lifeline utilities representatives at the Waikato and Bay of Plenty Lifeline Utilities Forum on 22nd August 2019 in Hamilton Gardens, Hamilton. The ECLIPSE Scenario Development Lifeline Utilities Workshop (ESDLUW) aimed to highlight that volcanic unrest at A-NZ's caldera volcanoes is a risk which can affect lifeline utilities organisations and that the scenario presented (ECLIPSE Scenario A) could be one of the possible forms this future unrest could take. The specific objectives of the ESDLUW were to;

- Raise awareness of unrest as an issue that can affect lifeline utilities organisations.
- Identify the impacts of unrest on these organisations.
- Identify the implications of these impacts on those organisations.

The ESDLUW involved stakeholders answering a series of questions in response to a volcanic unrest scenario in multi-disciplinary groups (*Appendix D*). These questions were developed prior to the workshop with consultation from the research team. Participants included representatives from a diverse range of organisations involved in disaster risk management in the Waikato and Bay of Plenty regions. Facilitators roamed around the room, rather than having one facilitator per group, to answer questions from participants, prompt discussions if they stalled, and mediate if necessary.

By presenting ECLIPSE Scenario A the workshop allowed participants to more clearly consider the impacts and the implications of the scenario on their respective organisations. Participants were specifically asked to look at the scenario from a strategic planning perspective as volcanic unrest is a highly uncertain and evolving phenomenon that could last up to decades before an eruption or a return to pre-unrest behaviour occurs (Newhall & Dzurisin, 1988; Potter, Scott & Jolly, 2012). This long-term perspective guided groups to look at the social and economic impacts of an event like this, rather than just the direct physical impacts of the geological hazards.

Similar to the ESDW in March, the ESDLUW enabled the research team to gain insight into the priorities, values and perspectives that drive decision-making for lifeline utilities organisations in response to caldera unrest.

2.3.4 ECLIPSE Scenario Framework Evaluation Interviews

The third and final stage of the framework was the review process for this research, which involved one-on-one semi-structured interviews with representatives across all the discipline groups originally approached in the ESDW and engaged throughout the research (*Table 2.1*). Participants selected for this stage of the review include leads of specific stakeholder groups that are part of the ECLIPSE programme, "task groups" and play an important role within A-NZ's disaster risk management. These task groups allow each stakeholder group to nominate one or more people to represent them by participating in regular task group activities, such as this research project, and report back to quarterly CAG meetings.

The ECLIPSE Scenario Framework Evaluation Interviews (ESFE Interviews) took place over December 2019 and January 2020. These ESFE Interviews aimed to evaluate the relevance and potential usefulness of the ECLIPSE Scenario Framework by working through the framework with the participants and then a scenario (either Scenario A or Scenario B; *Chapter 4*). These work-throughs were followed by a discussion around the framework and scenario, guided by questions outlined in a questionnaire (*Appendix E*). These questions were;

- What is your organisation's role, and responsibilities, in New Zealand volcanic disaster risk management?
- How would your organisation use the scenario?
- How useful and useable is the scenario for your organisations roles and responsibilities?
- Would your organisation use the scenario framework to create your own scenario(s)?
- For you organisation, what would be useful guidance for the use of the scenario framework?
- Would having a common suite of scenarios, accommodating different applications, be useful? If so, how might that be useful?

The method of semi-structured interviews was chosen for this part of the framework development process as it provides many benefits to qualitative research (Davidson & Tolich, 2003). Semi-structured interviews allow the researcher to guide the participant into particular topic areas but what specifics are discussed are dependent on the participant themselves. This is a powerful research technique where the topic of interest is particularly complex, such as volcanic risk management, and allows thematic analysis of the data (Davidson & Tolich, 2003; Pathak & Intratat, 2012).

The formatting and question design of the questionnaire (*Appendix E*) that guided the interview was based on theory by Davidson & Tolich (2003). They suggest that semi-structured interviews should open with simple, introductory questions that start the participant talking, followed by questions that link to themes that represent the research project's interests, with generic prompts from the interviewer within each of those themes/questions to ensure relevant detail on the topic is gained.

Prior to conducting the ESFE Interviews, an ethics application was made to the University of Canterbury Human Ethics Committee (2018), with the application approved on 9th December 2019 (*Appendix E*). As a result, participants were asked to complete a consent form prior to participating in their interview session. The interviews were recorded as "high-level notes" where the interviewer took notes throughout the interview, on a questionnaire sheet, and complied these notes after the interview. These notes were then emailed to participants, providing them with the opportunity to emphasise points stated, add points missed (upon reflection), or correct any errors. Participants had until the 30th January 2020 to do this.

The ESFE Interviews allowed stakeholders to have an in-depth look at the ECLIPSE Scenario Framework and either ECLIPSE Scenario A or B that had been developed out of the framework. This helped stakeholders specifically identify where they might utilise the framework and scenarios, why it would be useful in these contexts, and what guidance they might need in order to achieve this implementation. It also helped stakeholders identify the benefits of the framework and scenarios and where they could develop them further within their own agencies.

The ESDS Interviews enabled the research team to robustly evaluate the ECLIPSE Scenario Framework and ECLIPSE Scenarios, by reviewing interview statements and identifying themes across the interviews. These evaluations allowed the research to outline the benefits of the framework and scenarios, identify limitations, and make future recommendations for use and application of the research as well as where it could be developed further in future, within the ECLIPSE programme and/or externally within individual stakeholder agencies.

3 ECLIPSE Scenario Framework for Silicic Volcanism in Aotearoa-New Zealand

The first part of this chapter reports the findings from three stakeholder engagements, the ECLIPSE Scenario Development Workshop (ESDW), New Zealand Volcano Science Advisory Panel ECLIPSE Scenario Discussion Session (NZVSAP ESDS), and the ECLIPSE Scenario Development Lifeline Utilities Workshop (ESDLUW), undertaken throughout this research (*Section 3.1*), addressing part of Objective Three. This is followed by analysis and discussion of those findings and how they shaped the development of the ECLIPSE Scenario Framework, including in-depth explanation of why particular attributes were included within the framework (*Section 3.2*), addressing both Objectives Two and Three. The third part of this chapter describes the ECLIPSE Scenario Framework itself and addresses Objective Two (*Section 3.3*). The fourth part of this chapter (*Section 3.4*), reports the findings from the ECLIPSE Scenario Framework Evaluation Interviews, undertaken at the end of the research project's development timeframe, addressing part of Objective Three. This last section outlines how useful the scenario framework and scenarios were deemed by key stakeholders.

3.1 Assessing the scope and requirements for the ECLIPSE Scenario Framework from Stakeholder Engagement Findings

As noted above, *Section 3.1* presents the findings from the ESDW, the NZVSAP ESDS, and the ESDLUW. These findings are divided by application theme, driven from common themes pulled from disaster risk management literature (*Chapter 1*), and further divided by the themes' occurrence throughout the scenario framework development process; *Stage One*, which is primarily findings from the ESDW, and *Stage Two*, primarily findings from the NZVSAP ESDS and ESDLUW (*Figure 2.2* in *Chapter 2*). These findings are separated by the two stages as to illustrate how original statements made within the ESDW scoping workshop (Stage One) were reiterated and continuously emphasised throughout the development process or supported and further expanded on by new statements later on (which consisted of Stage Two, presenting versions of the framework and scenarios, and Stage Three, the evaluation in *Section 3.4*). This repetition demonstrated the importance of including different attributes in the framework and guided how and where these attributes should be included within the ECLIPSE Scenario Framework (*Figure 3.1*, outlined in *Section 3.3*).

3.1.1 Planning and Policy

3.1.1.1 Stage One

Almost all stakeholder groups during the ESDW identified the use of caldera scenarios as being useful to inform caldera volcano event disaster risk management planning, from reduction and mitigation, through readiness and response, to recovery (the 4 R's; NEMA, 2013). The stakeholders in particular noted their potential use to contribute to dynamic, adaptive pre-planning pathways (i.e. how actions should be taken to inform planning involving multiple agencies). CDEM and Lifelines listed contingency planning, exercise and training module development (such as "what-if" play-throughs), and response planning as specific examples of planning applications. CDEM emphasised the importance of using the caldera scenarios to inform recovery planning, stating the scenarios would help inform potential impacts across all environments (*Figure 1.2* in *Chapter 1*). As a result of this, CDEM requested the inclusion of indicators of what we might expect to see before or after a hazard occurs in the information provided alongside the scenarios, as this would help them to better prepare.

Industry suggested scenario use for informing adaptable land-use policies in the context of volcanic risk, urban vs. rural management plans, and cordon management, suggesting that by using the scenarios they could visualise what the conditions might look like and what actions they may need to implement in response. Industry and Lifelines further emphasised the importance of understanding, and increasing the understanding of, the potential impacts from these events as they help inform readiness and reduction planning.

Industry, Lifelines, and CDEM suggested including population statistics, such as demographic, employment, ethnicity, spatial location etc., as it would improve the scenarios in helping users to identify what industries may be affected and the number of people within those industries. Industry stated this would help inform the type and quantity of resources they may need to provide before, during, and after an event.

Iwi also suggested caldera scenario use for establishing robust recovery policy for volcanic event response, stating they thought it would be easier for the community to "bounce-back" if these actions were in place prior to an event.

All stakeholders stated the importance of including a variety of impacts in the scenarios to help inform planning and policy, such as direct vs. indirect, physical, unrest, social (e.g. behavioural), political, infrastructural, and (social and traditional) media influence impacts. Industry, Lifelines, GeoNet, and CDEM emphasised the importance of including the scale of the impacts, suggesting the use of metrics to measure intensity similar to that of earthquake shaking – Modified Mercalli Intensity (MMI) scale –, highlighting that the scale would be integrated into recovery plans, would help to better inform preparedness and mitigation measures, and would help reduce scaremongering among the public and media. CDEM specifically identified the importance of unrest hazards and impacts developed within the scenarios, such as ground deformation hazards and economic, psychosocial, and infrastructural impacts.

3.1.1.2 Stage Two

Using the scenarios for planning and policy applications was emphasised again throughout the ESDLUW, with stakeholders suggesting that they would develop and practice business continuity, preparedness, contingency, fuel, evacuation, and (cyber-)security plans within and between individual organisations in response to ECLIPSE Scenario A (*Chapter 4*). Stakeholders stated that developing various credible scenarios, with a range of outcomes and likelihoods, would assist in preparing response and contingency planning, particularly if populated on a decision-tree.

Stakeholders, in response to ECLIPSE Scenario A, identified that they would investigate the use of alternative network pathways and drive a potential shift in investments within affected areas, such as accelerating some planned projects (e.g. the Taupō control gate structure), but delaying other capital projects – opting for an increase in geotechnical maintenance or monitoring instead. Stakeholders stated that repairs on damaged infrastructure, such as substations affected by shaking or liquefaction, could extend several months and that maintenance would become a primary action throughout a prolonged unrest response. As a result, disruption to operations would be likely to occur in the short-term, with enhanced monitoring and inspections following in the short- to medium-term by organisations.

ESDLUW stakeholders further stated that, in response to prolonged unrest, discussions would open about the long-term service production, stating that there could be potential for reduction in services if populations migrated, reducing the demand for supply. Alongside this, evacuation plans for Lake Taupō shoreline communities would be reviewed and/or developed in preparation for long-term changes to the hydrology, including potential wave impacts and flooding infrastructure changes (e.g. flood-banks and dams). District Health Board (DHB) representatives specifically stated that it would be important to develop evacuation plans in the context of a welfare response with respect to neighbouring districts' actions as to make sure these districts did not become overwhelmed.

3.1.2 Community Engagement and Public Education

3.1.2.1 Stage One

All stakeholder groups identified the importance of using the scenarios for community engagement and public education applications. They emphasised that in order to reach these diverse groups of people, and to ensure the science was easily understood, the scenarios would need to have a minimal use of jargon, plain language, and easy to read formats. Stakeholders stated that it would be beneficial to have the scenarios relating to real experiences and stories, available in multiple languages (e.g. Te Reo Māori) and available within ECLIPSE's web resources.

Stakeholders suggested developing "seed" scenarios, as a tool for school-level education (amongst other sectors), to play-through, stating they would be beneficial as they would work to empower these traditionally excluded organisations and allow them to be more involved in planning and preparedness for caldera events.

CDEM and Iwi emphasised the importance of humanising the scenarios (e.g. roads acting as relationships) and relating the event to people and their stories, to help contextualise the events and their impacts. To achieve this, they suggested the inclusion of local knowledge of tangata whenua, relationships, stories of experiences from other hazards, kōrero, links to kinship ties, and the use of meaningful real-world examples. They identified that this would further help the scenarios become more relatable to more diverse audiences. Iwi specifically stated the caldera scenarios would be used within school outreach, possibly even implemented into school curriculum with a whānau focus, and would be used within story-telling.

CDEM, Lifelines, and Industry emphasised the importance of identifying potential impacts of losses of essential lifeline services, from a caldera event, and how these losses would impact households and individuals. This would help stakeholders to both understand the impacts and identify what information they may need to provide to the public. Industry and Lifelines stated that this understanding would help them prioritise response actions and enable them to clearly articulate how the hazards may affect those operators exposed.

GeoNet requested the inclusion of commonly overlooked hazards, such as ground deformation, earthquakes, gas, and geothermal activity, and that unrest-specific hazards would need to be carefully developed within the caldera scenarios to increase stakeholders and the public familiarity with these potential hazards. However, Research Scientists also requested that not all the activity prior to an eruption should be directly related to the volcano/volcanic unrest, as activity can occur within the TVZ without it directly relating to volcanic unrest and/or eruption.

3.1.2.2 Stage Two

ESDLUW stakeholders further emphasised the importance of using the caldera scenarios for community engagement and public education, stating that various scenarios would help prepare communities for what they may need to do throughout different stages of an event. Stakeholders specifically identified that in an unrest event, the public need, and want, to know about what is going on, therefore, they are more likely to already be engaging with official information, which would be an advantage to organisations providing that information.

Lifelines stated that, in response to an unrest event, they would hold more regular community meetings to help identify community leaders (if not already known), contact neighbouring districts, and address how they could collaboratively work to help each other. Lifelines and CDEM suggested the inclusion of similar global case studies to the caldera scenario(s), including consequences on people and infrastructure, authorities' actions, and communities' responses to both the events and authorities' actions.

Lifelines and CDEM stated that a key focus in response to an event would be bringing together key information for residents of affected areas, with DHB representatives suggesting that this would also include messaging on self-mental health (e.g. anxiety). They further stated that a coordinated response to the psychosocial impacts would be crucial to the DHB's effective response and that support for those within and around the affected areas, particularly those who had been displaced, would be vital. Furthermore, health stakeholders emphasised the importance of a communication focus on health and education around caldera unrest and what people should do in response. They stated that clear messages, with accurate and easily understood facts, would be crucial to inform the community.

3.1.3 Communication

3.1.3.1 Stage One

All stakeholders stated that caldera scenarios would be a good tool to inform and structure a broad range of communications around caldera volcanoes and potential events. They stated that these scenarios would significantly help with consistent messaging across organisations, but also ensure accessibility to caldera volcano information as each organisation could reach its target audience from the same core material, ensuring consistency in information at a base level but tailoring it to their specific needs. They further stated it would help structure conversations with other stakeholders they work with as well as educate stakeholders on gaps in their knowledge or plans. In order to achieve these applications, stakeholders suggested interactive formats of the scenarios such as cartoons, games, stories, models, videos, animations, and graphics, as these would help with uptake for communication and education purposes. These formats could be partnered with more traditional decision- or event-trees which would further help the scenarios become translatable across different contexts such as school-level education or stakeholder planning and/or policy development.

GeoNet identified the use of caldera scenarios within outreach and education, primarily by their Public Information Managers (PIMs), while Iwi identified that by using caldera scenarios and story-telling together, community resilience would benefit as people would have the opportunity to become more familiar with the hazards and impacts associated with caldera events in a less overwhelming way. Other stakeholders supported this, stating the caldera scenarios could enable more adaptable response from organisations, save people's lives, be a trigger to build relationships in advance of an event, and trigger community meetings to ensure everyone is getting the same message and understanding. CDEM specifically, suggested the caldera scenarios could be used to identify triggers for actions and engagement with other stakeholders and provide recommendations of when it would be best to make these connections.

CDEM suggested that the caldera scenarios could include impact-based actions and suggestions for their organisation to take, along with cues as to what other organisations, such as GeoNet or NEMA, would be doing. They stated this addition would help them shape and inform their own decision-making and identify what resources were/were not available to them. GeoNet similarly suggested including Volcanic Alert Bulletins (VABs) and Volcanic Alert Levels (VALs) in the scenarios, stating it would improve the scenario's similarity to real-world situations.

3.1.3.2 Stage Two

Communication was emphasised as an important theme further throughout the engagement process during both the NZVSAP ESDS and the ESDLUW.

Lifelines stated that their first response to a caldera unrest event (ECLIPSE Scenario A; *Chapter 4*) would be to gather information, such as scientific data, information about who had been affected and information about where staff were located within affected areas, from within their own organisations, other organisations, and the public. They stated that heightened communications between organisations often occurs as a result of active events and so they would act on this, activating groups amongst the various organisations to respond appropriately to the event, such as the Taupō District Council (TDC) Emergency Management Team and the Waikato Regional Council (WRC) Regional Resilience Team. They further stated they would ensure efficient communication across and within these groups as it would be crucial to an effective response.

Lifelines identified that consistent messaging would be a significant priority across all stakeholders and that the caldera scenarios may help in the creation of communication templates that would be developed and integrated across local and central government, lifelines utilities, and the media. They further identified that having a communication protocol would be essential to consistent messaging and a functioning response. They stated that hearing from other lifeline utilities organisations, including how they are managing uncertainty and physical changes, would be crucial to their effective response to an event.

NEMA, GeoNet, and Research Scientists also highlighted the importance of communication applications of the caldera scenarios, stating that they would help in attempting to manage and communicate uncertainty associated with caldera volcanoes. Stakeholders suggested the use of network-based or event-tree approaches to clearly demonstrate and translate the uncertainty.

Lifelines stated that communications between organisations would be crucial as all stakeholders would need to have shared input into decision-making due to their dependence on aspects of each other's services provided (e.g. telecommunication providers relies on power providers etc.). They further stated that in a prolonged event, Lifelines and CDEM would review how their groups were communicating throughout.

Lifelines identified that there would likely be a rise in demand for information from the public experiencing the event and they would likely look to the internet for this information. As a result, stakeholders stated that those services that provide access to the internet would need to continue to function throughout an event to reasonable level.

3.1.4 Science Gap Analysis and Testing Applications

3.1.4.1 Stage One

GeoNet and Research Scientists stated that the caldera scenarios could be used to help identify gaps in scientific hazard knowledge, such as where further research on hazard behaviour needs to be directed. They stated that this would help inform and frame research discussions around volcano systems models and caldera science in general. GeoNet and Research Scientists stated that because of this they would require a detailed science report alongside the caldera scenario(s) to outline and describe the science behind the scenario(s), including assumptions and limitations, which could help direct science research in future.

Industry, Lifelines, and GeoNet all identified the use of caldera scenarios for informing network resilience by workshopping the scenarios to test systems and identify gaps in redundancy or knowledge. Stakeholders specifically listed applications such as;

- Identifying the loss of infrastructure services from and on providers,
- Applying quality assurance/quality control (QA/QC) measures to plans,
- Evaluation of value chain resilience (on products such as kiwifruit or dairy),
- Testing and supporting research systems,
- Supporting and testing vent and hazard mapping, and
- Contributing to informing the design of monitoring network regimes.

In order to test the monitoring network regime, GeoNet further suggested the inclusion of the Volcano Monitoring Network as a specific attribute in the scenario framework.

3.1.4.2 Stage Two

GeoNet, Research Scientists, and NEMA stakeholders stated that the caldera scenarios, and approaches used to inform different parts of the scenario framework, could be sensitivity tested to improve their credibility and robustness.

3.1.5 Decision-making Resources

3.1.5.1 Stage One

Stakeholders identified that developing a range of caldera scenarios, which could identify common themes and issues across all the scenarios, would be beneficial as it could feed into preparedness and response planning. They emphasised that this range should accommodate different contexts, such as locations, duration, size etc., including maximum credible events, events likely to occur within our lifetime, manageable events (to reduce scaremongering amongst the public), and unrest-focused events.

Stakeholders suggested these scenarios could be built out of a modular, updateable framework, with the ability to change rapidly, stating that this framework would help to encourage dynamic, pathway thinking within disaster risk management. Stakeholders stated that the framework would need to be flexible and adjustable, possibly combined with event-trees to help visualise thinking, and potentially have the ability to be used in real-time response.

Stakeholders identified the importance of a well-developed, multi-parameter timeline of the scenario(s), detailing the hazards, impacts, hazard durations, seasonal occurrence, and snapshots of the different phases throughout the scenario – rather than just cumulative hazards or impacts at the end of the event. However, Research Scientists expressed caution in providing a detailed timeline, stating that it would need to be clear to users that time units as precise as hours and days would not be an achievable forecast in real-world events. Research Scientists further stated that these caldera scenarios would help to define parameters for making calls during events.

Stakeholders requested that GIS shapefiles and maps made within the scenarios should be available for individual stakeholder or community use, such as integration into RiskScape, which was strongly suggested by CDEM, and link to other models or forecasts, such as weather forecasts. These applications would require the files to have clear, concise metadata, as suggested by GeoNet, and a guide for use for those not as familiar with GIS systems, as suggested by Iwi.

CDEM stated that they would use the caldera scenarios to inform development and visualisation of what is happening throughout a caldera event and further inform evacuation, resource prioritisation and allocation, and communication planning. They further requested detailed hazard information, such as ash fall composition, and stated that knowing whether or not these details would change the impacts would help inform their risk management efforts. Similarly, Industry and Lifelines stated that understanding the hazard-impact correlations and where they occurred would be important to their disaster risk management. They stated that hazard forecasting would be beneficial to couple with weather forecasting to inform impacts related to seasonal changes.

3.1.5.2 Stage Two

Stakeholders, during the ESDLUW, identified that various scenarios could help identify trigger points for decisions and actions around resources and their functionality, such as the influence of physical phenomena, voluntary evacuation from potentially affected areas, or where population migration may occur in response to prolonged unrest. For example, Lifelines identified that residents may choose to voluntarily migrate out of affected areas and that understanding the potential triggers for this migration would be important to their organisations. However, they identified that some residents in affected areas may not be able to leave, due to emotional connections to the area or constraints by ability and resources (lower socio-economic groups), and these people would still require support from lifeline utilities service providers in those affected areas.

Lifelines stated that understanding how disruptions to their operations could occur as a result of loss of staff in affected areas would be important to informing their resource related decision-making, listing examples of medical staff leaving hospitals, GPs, pharmacies, and/or rest-homes, depleting healthcare resources for residents. DHB representatives stated these effects would cascade when combined with other impacts, such as an increased strain on mental health services from communities affected by prolonged unrest hazards. They stated having a scenario that details what might happen in this case would help them inform preparedness and contingencies.

Stakeholders identified that understanding the scale – national, regional, local – of economic disruption would be important to understand how different industries, such as tourism, agriculture etc., would be impacted by prolonged unrest, particularly in the short-term. They stated that these industries would likely experience some form of decline initially and that investments (in real estate markets, infrastructure, specific projects etc.) may be affected, particularly due to the long-term uncertainty associated with caldera unrest. Lifelines further identified that there would be a change in priorities across organisations, such as planned projects bought forward, and that the loss of supply in response to the unrest events could result in prices increasing over the short-term because of increased maintenance costs. They identified that decisions would need to be made regarding when their organisations' should look at building resilience, such as parallel networks, and who would lead this "recovery" in response to prolonged unrest.

Stakeholders identified that there were a limited number of societal actions and range of impact in the framework and ECLIPSE Scenario A (*Chapter 4*), stating it would be useful to continue to expand this part of the framework. Lifelines and CDEM stated that hazard forecasts, including likelihoods, the potential extent of each hazard, what may happen next for each hazard, and more detail on the individual hazards, would be beneficial for informing decision-making throughout a scenario, alongside more detailed impact information across all environments (*Figure 1.2* in *Chapter 1*). Stakeholders further requested information on the potential knock-on effects of impacts to adjacent districts and what interdependencies existed within lifeline utilities' operations within the scenario as well as how the framework was aiming to accommodate the temporal aspect of scenarios.

In response to ECLIPSE Scenario A, Lifelines and CDEM identified that prolonged unrest would at some point become the "new normal" with many service providers stated they would continue operating "business as usual" unless the physical impacts became more significant and that tackling uncertainty would be the most challenging factor to manage. Stakeholders identified that this new normal would influence migrations in the affected area, stating some people may move away initially, due to uncertainty, but could return if the unrest behaviour becomes the new normal. Lifelines also stated that a framework for decision-making in this new, uncertain environment, and who makes those decisions, would be useful.

Lifelines and CDEM stated that it would be useful to use the caldera scenarios to review what is happening during a real-world event against the scenarios to identify similarities and differences, helping stakeholders to respond more appropriately. This further scenario planning would also involve stakeholders seeking advice on the potential range of future scenarios that could influence their functionality.

GeoNet, Research Scientists, and NEMA stated that there would need to be guidance on how to use the scenario framework to develop scenarios, suggesting a "choose-your-own-adventure" style may further improve the uptake within non-physical science stakeholders.

3.2 Interpretation of Stakeholder Engagement Findings to inform the design of the ECLIPSE Scenario Framework

From the four stakeholder engagements throughout the research, four main themes for the ECLIPSE Scenario Framework became apparent;

1. that the physical phenomena aspect is a core part of developing a scenario,
2. the physical impacts are a core part of developing the scenario into application uses,
3. the uncertainty related to caldera volcano events is strongly characterised in the context of the unrest phenomena and psychosocial responses to that phenomena,
4. the impacts on the cultural environment are significantly different, due to differing perspectives of the "hazard" itself.

3.2.1 Physical Phenomena

Stakeholders strongly identified that the physical phenomena of a caldera scenario was core to developing scenarios and therefore the framework. CDEM, NEMA, Industry, Lifelines and Iwi stated that they would need a simple physical phenomena scenario, informed from scientists or by working alongside scientists to develop it, to then develop their impacts scenario(s) from. Research Scientists also emphasised the importance of including robust, credible physical phenomena but at a far more detailed level than all other groups. This illustrated that a simple narrative of physical phenomena was a base level requirement for inclusion within the framework. This would then allow whichever perspective (remaining simplistic or developed to a more detailed level) to be created from there. This physical phenomena was accommodated for in the ECLIPSE Scenario Framework by the *Hazard* section in *Figure 3.1*. The *Hazard* section aimed to characterise the volcano hazard by including four broad variables that help define volcanic events and inform the basis of decision-making. These variables are described below (*Sections 3.2.1.1 – 3.2.1.4*).

3.2.1.1 Volcanic Hazards

10 volcanic hazards that can potentially be experienced as part of caldera unrest and/or eruptions are listed within the *Volcanic Hazards* box in *Figure 3.1*. These hazards are standard inclusions when characterising a volcano globally and nationally and therefore included in the framework (GNS Science, 2010c). This was strongly supported by GeoNet and Research Scientists, during the ESDW, specifically requesting that commonly overlooked hazards, such as ground deformation, gas, and seismicity, should be included in the framework. The variety of hazards was further supported by Industry, Lifelines, and CDEM stakeholders, who emphasised the importance of scenarios that involved multi-hazard interactions and challenges.

3.2.1.2 Event Size

The potential *Event Size* (*Figure 3.1*) is measured by the Volcanic Unrest Index (VUI; Potter et al., 2015a) and the Volcanic Explosivity Index (VEI; USGS, 2017; Newhall & Self, 1982). Traditionally, there has always been more of an emphasis on eruptions rather than volcanic unrest, with caldera unrest management an underdeveloped field of volcanic risk management. However, it is important to understand how unrest, and its associated hazards, can impact surrounding environments and treat it as its own issue (Woo, 2018; Potter, Scott & Jolly, 2012). VEI is a common way for volcanic events to be defined globally and helps to give an understanding to the size of a potential event by comparing it to other global and national case studies (such as the 2008 Chaitén eruption, which was a VEI 4, or the Kaharoa eruption in 1314 AD which was VEI 5) – something which was explicitly requested by CDEM and Iwi during the ESDW.

3.2.1.3 Geographic Domain

Geographic Domain, in *Figure 3.1*, addresses the potential location or source of the volcanic event. These boundaries are first defined by previous research that has identified eight previous caldera centre boundaries (*Section 1.4* in *Chapter 1*; Froggatt, 1997; Nairn, 1993). However, because these centres sit within a larger active volcanic zone (the TVZ; *Figure 1.5*), areas within this wider zone, but outside of the previous caldera centre boundaries, are still considered as sources of potential unrest and/or eruption (Potter, Scott & Jolly, 2012). This location variability was identified by GeoNet and Research Scientists throughout engagements.

3.2.1.4 Magma Composition

Magma Composition, in *Figure 3.1*, was included as, although most of the volcanic events from the TVZ's caldera volcanoes have been rhyolitic, there is still the potential for variation in magma composition. This has been demonstrated in previous events, most recently by the 1886 Tarawera eruption which consisted of more basaltic magma than rhyolitic (Nairn, 1993). This inclusion of variability was identified within the ESDW by Research Scientists.

3.2.2 Physical Impacts

What was apparent from all stakeholder engagements was that the natural phenomena presented by caldera volcanoes was important to the core structure of potential scenarios (as highlighted in *Section 3.1*). However, there was a split between Research Scientists, who wanted some extremely detailed purely hazard scenarios, and all other stakeholder groups, who wanted robust impact scenarios in response to a "simpler" hazard scenario. As a result, the ECLIPSE Scenario Framework became a useful tool to incorporate the physical phenomena but also accommodate the modularity of different impact scenarios driven from different perspectives of interest (the right-hand side of the framework; *Figure 3.1*). This is important to highlight as the hazard does have to be present in the first place in order to create the scenario, however, the level of detail those hazards need to have depends on the purpose of the scenario's creation. For example, if CDEM were to develop a scenario to inform evacuation planning, they may only need to know that hazards currently occurring have imposed a 20km no-go zone from the centre of Lake Taupō and can inform their response decisions and actions from there.

The physical impacts characterisation was accommodated within the ECLIPSE Scenario Framework by the *Exposure* and *Vulnerability* sections in *Figure 3.1*. There can be many different kinds of impacts as a consequence of caldera events, these sections of the framework aimed to cover spatial and physical attributes of assets and populations potentially affected by caldera hazards. Several initial variables were considered for inclusion in the framework and refined or expanded upon during stakeholder reviews throughout August of 2019 (*Section 2.3* in *Chapter 2*). Due to the multitude of potential variables that could have been included here onwards, it is important to acknowledge that these variables are, firstly, broad, commonly considered variables within disaster risk management and, secondly, not the only variables that could or should be included in future versions of the framework or within scenarios. The aim with providing broad starting variables is that individual stakeholders, who are subject matter experts within certain fields, can further populate and refine sections of the framework itself, which in turn, makes the information more credible, reliable and relevant. These broad variables are described below (*Sections 3.2.2.1 – 3.2.2.2*).

3.2.2.1 Built Environment

Having a spatial understanding of the built environment is important, alongside understanding the vulnerability of these built assets to various hazards (such as ash fall or ground shaking), to help inform preparedness, response and contingency measures (Loughlin et al., 2015). The built environment attributes across the *Exposure* and *Vulnerability* sections of the framework accommodate this by allowing stakeholders, subject matter experts, to inform the vulnerability and impact thresholds. This threshold accommodation was heavily supported by Lifelines throughout the ESDLUW. The more specific attributes are discussed further throughout *Sections 3.2.2.1.1-3.2.2.1.4* below.

3.2.2.1.1 Community Centres

Community Centres were included as they are often places that are used by emergency management officials to set up relief or evacuation centres during crises and used to run workshops and exercises during non-crisis. The inclusion of this was supported by stakeholders during the ESDLUW, where Lifelines stated that mapping the locations of important assets, like marae or community gathering points, was important to their understanding and response to an event. These centres also play integral roles in a community's functionality and sense of community, identified by NEMA during the NZVSAP ESDS.

3.2.2.1.2 Emergency Services

Emergency Services accommodates emergency responders, such as fire, police, search and rescue, as well as CDEM Groups, at both regional and district levels. It helps to build spatial awareness as to where resources may come from during an emergency and whether they may be compromised (due to proximity to hazards or lack of operational services). As well as providing staff and vehicle numbers, for example, to give a comprehensive understanding of what resources may or may not be available throughout different scenarios. The need for spatial intelligence was identified within the ESDW by Industry and Lifelines and the need for resource understanding (in terms of staff) was identified by DHB representatives during the ESDLUW.

3.2.2.1.3 Volcano Monitoring

The GeoNet Volcano Monitoring Network was included within the framework for two primary reasons; firstly, previous events, both globally and locally, have shown that it is significantly important to have a functioning monitoring system in place, particularly during unrest, but also during response (see the successful management of the Pinatubo eruption in 1991; Pappas, 2011; Newhall & Solidum, 2017). Secondly, it was identified by GeoNet, during the ESDW, that the monitoring network would need to be included as it was an important part of how they inform their decision-making (such as setting VALs and producing VABs), which therefore informs other stakeholders decision-making – as reflected by CDEM who stated they would use these GeoNet resources to inform their response actions.

3.2.2.1.4 Core Lifeline Utilities: Telecommunications, Water, Transport, Electricity

Core Lifelines Utilities are required for a functioning community and therefore are important for inclusion in the ECLIPSE Scenario Framework. Furthermore, Industry and Lifelines stated, during the ESDW, that having and understanding of the potential loss of services during an event would help them to better develop preparedness strategies.

An understanding of the spatial locations of telecommunications (such as cell towers and lines) is significantly important pre-, during and post-crisis as a lot of decision-making, if not all, is reliant on communications between authorities, scientists, emergency responders, media and the public. Being able to anticipate that normal telecommunication functions may not be available can have a significant influence of the efficiency in response to an event, particularly in the immediate to short-term.

Three waters, representing drinking water (potable), stormwater, and wastewater is critical in understanding the potential impacts felt by a community and in helping inform where resources should and could be allocated throughout a scenario.

Transport encapsulates the four main modes of transportation of individuals, goods, and services in A-NZ. The spatial mapping aspect includes roads, tracks etc. as well as ports, airspaces and the number of vehicles available. This is not only beneficial for understanding within transport providers, CDEM Group evacuation planning or police cordon management, but is also beneficial for GeoNet as it helps them inform whether or not campaign monitoring (specialised monitoring in response to abnormal behaviour) would be a viable option and where they may be able to receive more data from.

Electricity, including hydro-, wind, solar, geothermal, biomass and diesel/gas, is critical for both providers and receivers of power. Throughout the central North Island there are several energy providers that would be in some way affected by caldera phenomena and understanding where these systems may be impacted will help providers to prepare contingency and alternative operational plans and strategies (*Section 3.1.1*). It helps other lifeline utilities providers, such as DHBs and hospitals, to gauge whether or not they may need to rely on back-up systems, such as generators.

3.2.2.2 Natural Environment

The natural environment should also be considered when characterising potential impacts from caldera events as some of the decision-making made in previous environments can be heavily influenced by what the natural environment is experiencing. For example, soil health can have a significant influence on the agricultural industry in the affected areas or can impact the livelihoods of rural and Māori communities (Loughlin et al., 2015), as emphasised by Industry and Iwi during the ESDW.

3.2.3 Uncertainty Defined by Unrest and Psychosocial Contexts

The uncertainty associated with caldera volcanoes was a strong theme from all stakeholders across all engagements, with the uncertainty being characterised in two broad categories; the occurrence of unrest phenomena and psychosocial responses to that phenomena. This uncertainty was accommodated within the ECLIPSE Scenario Framework by the *Exposure* and *Vulnerability* sections in *Figure 3.1*. Alongside the spatial and physical attributes of assets and populations, these sections further aimed to cover societal and economic implications of impacts from these potential caldera hazards. Specifically relevant to this uncertainty theme, the *Vulnerability* section of the framework was designed to reflect NEMA's Resilience Environments (*Figure 1.2* in *Chapter 1*; MCDEM, 2018) to better address the variability within vulnerability and the influence different environments have on impacts from events and risk resilience. These uncertainty characteristics are described below (*Sections 3.2.3.1 – 3.2.3.2*).

3.2.3.1 Social Environment

Understanding and accommodating for social impacts from caldera events is an important part of understanding the risk and therefore important to be included within the ECLIPSE Scenario Framework. Acknowledging that these built centres, such as community and education centres, act as more than just a location to a community is important in understanding the stresses and strains they may experience prior to, during, and after a caldera event. This was emphasised by NEMA, at the NZVSAP ESDS, stating that these centres play an integral role in how a community comes together and remains resilient throughout crisis.

3.2.3.1.1 Population

Spatial awareness of populations potentially affected by caldera hazards is crucial in volcanic risk management as it helps inform evacuation planning for CDEM Groups, cordon management for police and where potentially affected people may be for emergency responders, particularly in the immediate-term. Understanding the population in other ways that make it vulnerable, such as demographics, employment, and ethnicity, is also important and was identified by Industry, Lifelines, and CDEM during the ESDW. Industry specifically identified that these attributes help to identify what industries could be affected by potential events and how many people within those industries may be affected. They further stated this would help give an indication on what and where to provide assistance, such as financial aid.

3.2.3.2 Economic Environment

Economic environments can be heavily impacted by caldera events, particularly by unrest where the uncertainty of whether or not an eruption will occur can influence strategic planning and long-term decision-making. The economic impacts can range from localised business losses to national scale market and industry changes and is therefore an important inclusion in the framework when characterising impacts and, ultimately, risk. NEMA, during NZVSAP ESDS, emphasised the importance of quantifying and mitigating the economic stresses and impacts from caldera unrest for A-NZ as a nation. Industry, during the ESDW, stated that characterising the potential economic impacts would help them understand what financial aid they may need to provide, particularly to rural communities, throughout a scenario. This was further supported by Lifelines, at both the ESDW and the ESDLUW, stating that understanding the potential economic impacts would help inform strategic, alternative pathways, and contingency planning.

3.2.4 Cultural Environment Impacts

The fourth theme that was essential for the ECLIPSE Scenario Framework to accommodate was the difference in cultural perspectives to caldera volcanoes and their events. The impacts to the cultural environment proved to be significantly different than those of other environments as expressed by Iwi throughout the research's engagements. This cultural difference was accommodated within the ECLIPSE Scenario Framework by the *Vulnerability* section in *Figure 3.1*, specifically the *Cultural Environment* box, mirrored from NEMA's Resilience Environments (*Figure 1.2* in *Chapter 1*; MCDEM, 2018).

As A-NZ is a multi-cultural society, with bi-cultural obligations (MCDEM, 2018), modern disaster risk management approaches must acknowledge the importance of increasing involvement from indigenous communities and more culturally diverse perspectives (Kearns & Joseph, 1997). The needs of different cultural communities vary across communities prior to, during, and post-event and therefore, it was important a space for this was provided within the ECLIPSE Scenario Framework (Loughlin et al., 2015). Acknowledging these cultural influences on decision-making was identified during the ESDW with Iwi stating that allowing the scenarios to link to kinship ties and family stories was crucial to making sure the scenarios were useful and useable for Māori communities. Iwi, CDEM, and Industry further stated that this inclusion would help build a more realistic picture of a community level response to an event.

3.3 Design and Development of the ECLIPSE Scenario Framework

This section presents the ECLIPSE Scenario Framework as a tool to contribute to A-NZ's disaster risk management. This framework uses the learnings from the stakeholder engagement approach, specifically including the physical phenomena and impact requests from stakeholders expressed throughout the four engagements as part of this research (*Section 3.2*). The framework is further informed by the literature reviewed throughout *Chapters 1* and *2*. This section also addresses Objective Two of the thesis; to develop methods for disaster hazard and impact scenario development for silicic volcanism through the development of a modular, adaptable hazard and impact scenario framework for A-NZ's caldera volcanoes; the ECLIPSE Scenario Framework (*Figure 3.1*). The framework works by

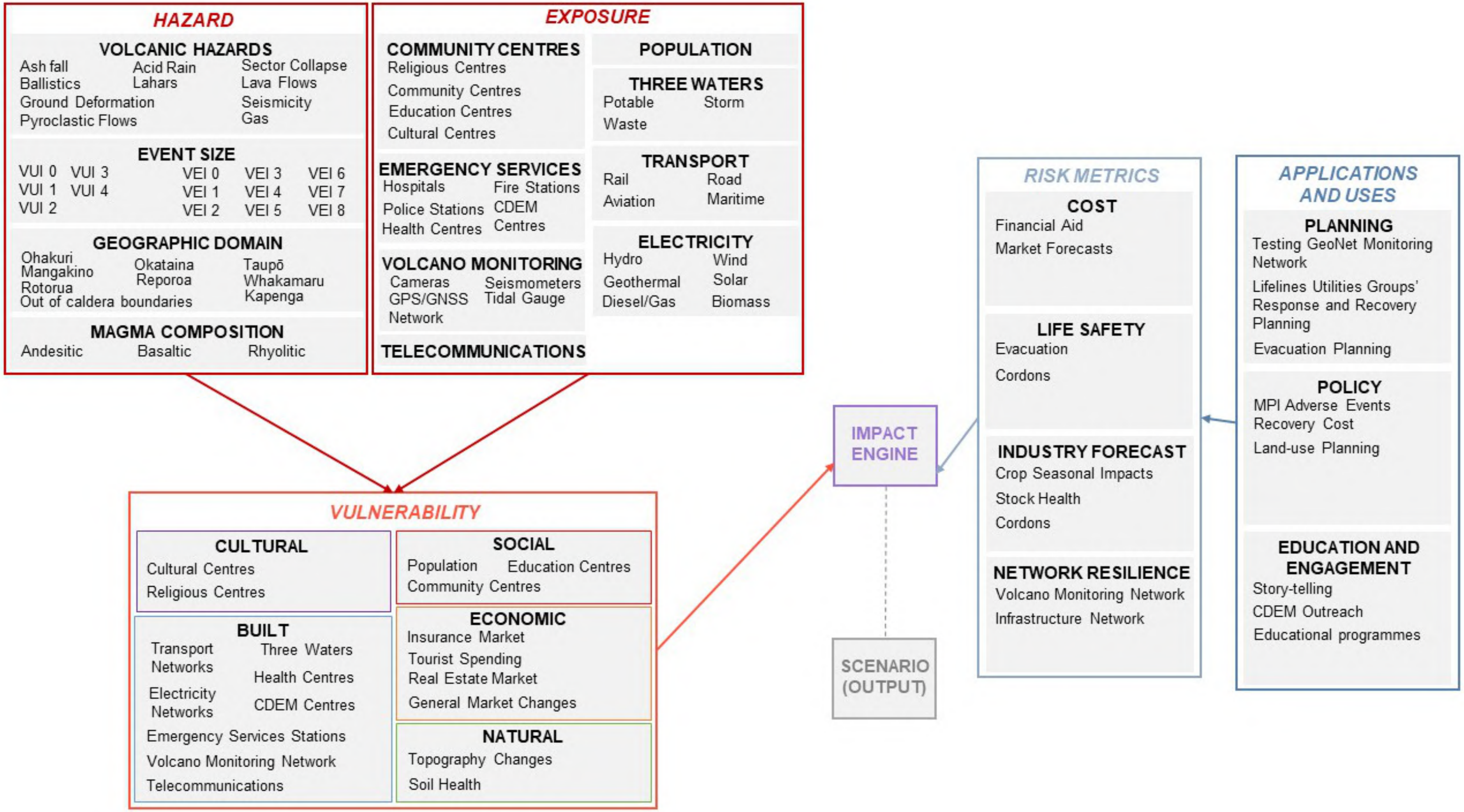

Figure 3.1: ECLIPSE Scenario Framework for Silicic Volcanism in A-NZ (Version 2.2).

combining integral themes and attributes of caldera volcano hazards and impacts alongside application and attribute requirements from a diverse range of sectors of disaster risk management in A-NZ into one coherent form.

The structure of the left side of the ECLIPSE Scenario Framework is derived from common, globally accepted disaster risk practice, which is a function of hazard, exposure and vulnerability (*Figure 1.6* in *Chapter 1*; UNDRR, 2015; Loughlin et al., 2015; GFDRR, 2016). Within disaster risk management there is often an inherent level of "acceptable risk" when dealing with low frequency, but high consequence, natural hazards; defined as *"the level of potential losses that a society or community considers tolerable given existing social, economic, political, cultural, technical and environmental conditions*" by the UNDRR (2016, p.14). This acceptable risk is often the basis for which emergency management plans are developed from as these plans are designed to be put into action once this level of acceptable risk has been exceeded (Jolly & de la Cruz, 2015). This approach of using impact-based thresholds (*Sections 3.2.2-3.2.4*), alongside geophysical thresholds (*Section 3.2.1*), makes the ECLIPSE Scenario Framework and ECLIPSE scenarios more useful as the thresholds significantly influence the management of the event and tend to be easier to define by stakeholders.

The structure of the right side of the framework is derived from;

- Literature (outlined in *Chapter 1*, *Section 1.6.2*), that supports these applications and uses and risk metrics included in the framework (*Figure 3.1*),
- Previous research experiences (outlined in *Chapter 1*, *Section 1.6.3*), that have highlighted structures should reflect the collaborative nature of the methodology behind scenarios and the importance of diversity in scenarios" applications and uses,
- Stakeholder engagements (outlined earlier in *Section 3.1*), that guided specific attributes added, particularly in the applications and uses column (in *Figure 3.1*).

This part of the framework accommodates the diversity in applications and uses of potential scenarios and how these applications and uses may be defined through broader high-level risk metrics.

The *Risk Metrics* column of the ECLIPSE Scenario Framework (*Figure 3.1*) acts to define how stakeholders may choose to measure hazards and impacts within the scenario. This could be done by unquantified measurements (using broad terms such as "High Risk") or quantifiable measurements (such as hard metrics, like potential fatality numbers, or non-hard metrics, such as general societal risk). This column allows stakeholders to look at the themes (applications and uses) and then decide what impact they specifically want measured out of those themes. This method follows the International Organisation for Standardisation (ISO) 31,000's (2009) risk assessment approach, where stakeholders identify their impacts, analyse their relevant parameters (the left side of the framework), and evaluate the impacts (and their risk) in the context of risk metrics. This allows stakeholders to specifically focus on what is important to their sector, for example, Industry may want to focus on response planning in the context of financial aid, focusing on how many employees of a particular primary industry may need subsidies following weeks of disruption from caldera unrest (a suggestion from the ESDW). Similarly, Lifelines may want to inform response planning but focus on network resilience rather than the cost of recovery, even though neither impact is mutually exclusive and both are relevant to Lifelines' functionality, the drive behind developing a specific scenario may be more focused on one or the other.

Potential *Applications and Uses* of the ECLIPSE Scenario Framework and ECLIPSE Scenarios were identified in the ESDW and further refined, prioritised or expanded upon throughout the NZVSAP ESDS, ESDLUW and ESFE Interviews. The specific examples listed in *Figure 3.1* were identified within these stakeholder engagements, however, they do not represent a complete list of applications and uses, rather a broad overview. These potential applications and uses fell under three broad categories; planning, policy, and education and engagement, again however, these could and should be further expanded beyond this research project.

The *Impact Engine* section of the ECLIPSE Scenario Framework acts as an engine room, combining themes and attributes from both sides of the framework, developing and refining them into a scenario. This scenario is then provided as an *Output* or product of the *Impact Engine* and therefore, the overall framework.

3.4 Evaluation of the ECLIPSE Scenario Framework and ECLIPSE Scenarios

This section of *Chapter 3* reports the findings from the ECLIPSE Scenario Framework Evaluation (ESFE) Interviews, where stakeholders were shown the ECLIPSE Scenario Framework (*Figure 3.1*) and either ECLIPSE Scenario A or ECLIPSE Scenario B (*Chapter 4*) and then taken through a questionnaire (*Appendix E*). These findings are divided by application theme (*Sections 3.4.1-3.4.5*), similar to that of *Section 3.1*.

Industry, GeoNet, CDEM, and NEMA, stated that they would use and implement the ECLIPSE Scenario Framework and ECLIPSE Scenarios within their organisations, with each stakeholder further stating they would make some form of adaption to the resources. This indicated that the framework and scenarios developed had successfully provided a base or first step for further scenario development to continue to develop from. Stakeholders emphasised this usefulness of the framework and scenarios within their applications and uses, stating they could continue to develop further, more in-depth scenarios and listed potential applications of the framework and scenarios, which are detailed in *Sections 3.4.1-3.4.5*.

3.4.1 Planning and Policy

Industry stated that they would use the caldera scenarios to drive and inform response and recovery planning, particularly adaptable plans, as plans can often go out the window in emergencies, therefore, decision-makers must be able to adapt to evolving situations. Industry stated the scenarios would help visualise and workshop this adaptability and could work to present as many variations of events as possible so that most possibilities can be accounted for. CDEM also stated that they would use the knowledge presented in the caldera scenarios to inform planning and readiness and build reduction activities from. They stated they would achieve this by using the scenarios to increase the understanding of potential impacts from volcanic events and develop an unrest response framework, stating these scenarios and the ECLIPSE Scenario Framework are the first step in this response development process. NEMA and GeoNet further stated they would use the caldera scenarios to inform volcanic planning, indicating they would use them for internal training and education throughout teams such as operations, planning, duty, and capability.

NEMA further stated that, due to the inherent uncertainty with caldera volcanoes, it is good to have the ECLIPSE Scenario Framework to emphasise the importance of not getting fixated on a single event because the outcomes can be so different across different events. They stated this would help not limit the awareness and preparedness measures towards caldera volcanoes.

Industry and CDEM stated that they would use the caldera scenarios to help inform resource planning. Industry specifically suggested their use in identifying what resources might be needed throughout events and where development could occur in these plans. They further stated the scenarios would be used to help discuss how best to address the consequences of an event with respect to existing resources and what extra resources may be needed in future.

GeoNet and Industry stated that they would use the caldera scenarios to inform contingency and evacuation planning, with Industry specifically stating they would be used to inform decisions from a welfare perspective about livestock evacuations.

CDEM further stated that they would use the caldera scenarios to attempt to influence policy decisions and implementations if and where needed, such as building code standards.

3.4.2 Community Engagement and Public Education

CDEM, NEMA, and GeoNet stated they would use the caldera scenarios to inform some of the content included in public education activities and resources, such as informative posters, public messaging, with PIMs, and in organisational outreach. CDEM specifically suggested the focus should be on building awareness around caldera hazards and impacts rather than scaring people and that the scenarios would be used as a communication pathway within communities and with iwi partners. Industry stated that they would use the caldera scenarios to help inform and provide the best information to their organisations from scientists, which they could then provide to their relevant public audiences, particularly rural communities. Industry stated this would help improve organisational awareness to volcanic episodes and what their potential consequences may be.

CDEM stated that the caldera scenarios were a good way to demonstrate how A-NZ might likely experience caldera volcano events, including helping to understand the degree of uncertainty and length of time unrest could involve and the degree of interruption caused as a result. NEMA further stated the scenarios would be useful in increasing understanding and awareness of caldera unrest and education on unrest and/or eruption from caldera volcanoes, particularly such as what patterns of unrest could involve, especially across the long-term. CDEM and NEMA both stated that the more visual aspect of the scenarios, such as the timelines, graphs, and maps, were particularly useful for communications and public messaging purposes.

NEMA further stated that the caldera scenario would be used to inform national warning systems training and that having a suite of scenarios from a common methodology would be useful as, assuming these are proofread by the same, diverse groups every time, it would ensure everyone was on the same page and agreed with the information presented. This would directly benefit public messaging and education, particularly during an event when the demand for information is high and expected to occur somewhat rapidly. This would also allow scenarios to be specifically developed in respect to scaremongering or public relations focused outputs.

3.4.3 Communication

Industry, GeoNet, and NEMA stated that the scenarios would be used as a communication tool working to communicate the difference between events and series of hazards and/or impacts and the uncertainty associated with each step.

Industry, NEMA, and CDEM stated that they would use the scenarios to initiate and support discussions with external stakeholders and establish relationships and contacts with new external stakeholders where they were missing, prior to an event. These discussions would cover topics such as what these partners can be prepared for (e.g. land-use planning) and how they might respond collaboratively and could be undertaken through channels such as exercises and training workshops. NEMA stated these organisations could include the Caldera Advisory Group (CAG) or insurance companies (and other economic focused organisations), to gauge different perspectives on impacts from an event. Industry highlighted that this would help improve synergy while reacting and responding to an event. CDEM stated these scenarios would be used to inform the balance of communications to suit the situation at hand and taking the necessary actions to ensure this communication balance takes place.

GeoNet and NEMA stated that the caldera scenarios would also be used to open discussions internally within organisations and to prompt internal education, such as reviews of what has been done in the past and how that can be used in future. GeoNet stated these discussions could centre on science topics that may be more divisive issues or operational decisions, such as Volcanic Alert Levels (VALs) or how to monitor volcanic phenomena.

NEMA also stated the scenarios could be used to evaluate and test the emergency management system as a whole, across all diverse environments (*Figure 1.2*) and stakeholders.

CDEM and NEMA highlighted that the benefit of having a common methodology behind the scenarios (via the framework) ensured that planning and discussions around caldera events would be more streamlined and avoid confusion, ensuring everyone is on the same page. They stated that without the framework, there is a potential for individual organisations to rush off and make their own scenarios that may not necessarily be relevant or focus on only one evolution of events. CDEM stated it was good to have the guidance of the framework and that it was important that groups work on these scenarios together.

NEMA stated that, by using the same suite of scenarios and framework, there are more organisations using the same base material which directly benefits the coordination of decisions and actions and ensures consistency across groups. Including social and cultural impacts focused scenarios would also be good to centre discussions around, which the framework provides the basis for the start of, with CDEM stating this would help anchor people in the people-focused impacts of caldera volcano impacts, rather than physical or natural environments. By using this co-production method, it would also help groups understand how their external partners are using the scenarios, further informing their own development actions and minimising the duplication of tasks.

3.4.4 Science Gap Analysis and Testing Applications

CDEM stated that the caldera scenarios were useful in demonstrating what has been done so far, in terms of caldera events, and was a huge step forwards and a good start for the development of caldera volcano scenarios. These scenarios and framework can be built onto in the next stages of development.

Industry stated that the caldera scenarios were useful in showing gaps in previous thinking and resilience. They stated these would be used to further highlight gaps in the disaster risk management and caldera volcano knowledge during non-crisis times. The goal would then be to inform and educate organisations on these gaps, and work to fill them. CDEM complemented this, stating that the common methodology behind the framework and scenarios allowed them to robustly test the adaptability to these events, especially caldera unrest.

3.4.5 Decision-making Resources

GeoNet stated that the ECLIPSE Scenario Framework and ECLIPSE Scenarios were a valuable resource for disaster risk management, the key is to make sure they are used across organisations. They stated that having a common method for development across the framework and scenarios was beneficial as it enabled them to think about different possibilities, with CDEM stating that this suite/framework already established saves time and resources for them. CDEM further stated that, rather than entirely different scenarios, development could be focused on different branches off the same base scenario/starting point, like a decision-tree format. This would allow CDEM to address and explore the variability of hazards and impacts, specifically cascading hazards and impacts.

CDEM stated they would use the caldera scenarios to manage uncertainty in regards to caldera unrest, as they see unrest uncertainty as their biggest challenge for caldera event management. They stated they would further develop the scenarios with specific focuses such as involving industry stakeholders to further develop singular boxes/attributes from within the scenarios (timelines; *Figures 4.1.2 and 4.2.1* in *Chapter 4*).

Industry and CDEM stated that a potential credible suite of scenarios would need to include likelihoods (e.g. what is possible in a person's lifetime, maximum vs. minimum etc.), impact-focused scenarios (helping to identify the trigger points for management decisions), and best case vs. worst case scenarios (which could be in terms of the overall event or the individual hazards e.g. pyroclastic flows). They stated that a novel idea would be to have a scenario that focused on "distracting elements" such as a "rogue scientist" element, which would be useful to determine the efficiency of focus by organisations and teach them to not be distracted during response. Industry specifically stated that a more social element focused scenario would be interesting for them to workshop and implement.

3.4.6 Discussion on the usefulness and guidance for the use of the ECLIPSE Scenario Framework and ECLIPSE Scenarios by key stakeholders

Overall, all stakeholders interviewed during the ESFE Interviews stated that their organisation would use either the ECLIPSE Scenario Framework and/or the ECLIPSE Scenarios in future disaster risk management. All stakeholders stated that they could use these resources as the first step in comprehensively developing or refining more disaster risk management strategies across their diverse applications and organisations. Each organisation represented during the interviews was asked what they would need in order to use the resources, their responses are reported below (*Sections 3.4.61-3.4.6.4*; divided by organisation rather than theme).

3.4.6.1 Regional Civil Defence Emergency Management Groups

CDEM stated that they could focus on further developing specific community impact scenarios, lifelines impact scenarios, and far-reaching event scenarios, for example. They also stated that having the data (such as geospatial or statistical) already implemented in the framework attributes would make them much more inclined to use it than if they were to have to find it themselves. CDEM stated that in order to use the framework and scenarios they would need guidance in the form of explanations of the terminology used, so it is clear and not misinterpreted, and exemplars of what has been done with the current framework.

3.4.6.2 National Emergency Management Agency

NEMA stated they could use the framework to develop scenarios for exercises and possibly create scenarios for testing responses with more specific groups, such as economic stakeholders or the NZVSAP. NEMA stated that in order to use the framework and scenarios they would need to have a clear understanding of the assumptions made within them, the justification for these assumptions, and an understanding of what attributes have been modelled or just formulated at random, e.g. was an ash fall model run for the scenario or was an area of ash coverage chosen by the developer.

3.4.6.3 Industry

Industry stated that they would likely still need some assistance if they were to undertake developing a detailed hazard scenario but that the impacts could be informed by their organisations provided that they have been given or can find basic hazard information. In order to use the framework and scenarios, Industry stated that the more transparent, concise information provided, the more useful the resources would be for preparing and responding with. They suggested this informational guidance could include case studies from volcanoes similar to A-NZ's caldera volcanoes, including the lessons learnt and what went well/not well in those cases, which would help provide an idea of what to follow for their decision-making.

3.4.6.4 GeoNet

GeoNet stated that they would use the framework and scenarios with some adaptions, such as shorter timeframe scenarios ("snapshot" scenarios). In order to use the framework and scenarios, GeoNet stated the resources within the scenarios, such as timelines, maps, and shapefiles, would need to be available and ready to use for organisations and individuals. These resources would need to be clearly labelled and linked to the scenario (e.g. good metadata) and the addition of a "how to use" manual would be beneficial.

3.4.7 Recommendations following the ECLIPSE Scenario Framework Evaluation Interviews

Due to the time constraints for this project no changes from the stakeholder feedback was implemented on the version of the framework presented in *Section 3.3* and *Figure 3.1*. However, recommendations for future versions of the framework, based on these evaluation interviews are detailed below (with general recommendations outlined in *Chapter 5*).

All stakeholder interviewed suggested that understanding the flow of impacts, as much as the flow of physical hazards, was an important aspect of the framework and scenarios and, therefore, should be further developed. CDEM and GeoNet stated that the addition of impacts on the built environment (such as fuel suppliers, cordoned areas, and transport) would improve the scenario(s), with Industry stating the addition of impacts on the natural environment (such as pasture smothering from ash fall) would also improve the usability of the scenario(s). CDEM and NEMA also stated that the economic impacts should be more fleshed out in future development of the framework and scenarios. All stakeholders interviewed also highlighted the lack of detailed social and cultural impacts and that future work should also be driven in these directions, suggesting inclusions such as a welfare lens on the scenario.

CDEM and Industry suggested the addition of videos and images from historic events into the scenarios in addition to the mapped hazard extents (shown in *Chapter 4*).

NEMA, Industry and CDEM all suggested further inclusion of what decisions are being made by other organisations throughout the scenarios (similar to that of the VALs shown in the scenarios in *Chapter 4*). Industry stated this would help gauge what discussions might be going on at each stage of the event and allows them to form recommendations for actions, e.g. planning livestock evacuations based off police cordons informed by CDEM decisions. CDEM stated that decision points throughout the scenario(s) would improve it even more and help with the application into readiness, preparedness, and response planning. NEMA stated that most of the areas for improvement in the current framework and scenarios came from questions or perspectives that could be informed with further development with specific stakeholders to build narratives from those organisational perspectives.

The main recommendations for specific future developments are summarised in the points below;

- Develop the impacts on the built, social, cultural, and economic environments further – including specific relevant stakeholders and subject matter experts.
- Develop a narrative for potential organisational decision points throughout the scenarios (beyond the VALs already included).
- Partner the scenarios with imagery and videos from historical events and global case studies.

4 ECLIPSE CALDERA SCENARIOS

This chapter details the two scenarios developed as a result of the ECLIPSE Scenario Framework (*Chapter 3*); ECLIPSE Scenario A: The Taupō Unrest Scenario and ECLIPSE Scenario B: The Taupō Eruption Scenario (*Sections 4.1 & 4.2* respectively). Each scenario section outlines the justification for developing each scenario (both from literature and data collected throughout stakeholder engagements; *Sections 4.1.1 & 4.2.1*), what events are involved in each scenario (*Sections 4.1.2 & 4.2.2*), and how each scenario plays out, including resources developed for end-user use of the scenario (*Sections 4.1.3 & 4.2.3*). The workflows for implementing attributes from the ECLIPSE Scenario Framework into these ECLIPSE Scenarios is outlined in *Appendix G*.

4.1 ECLIPSE SCENARIO A: THE TAUPŌ UNREST SCENARIO

ECLIPSE Scenario A: Taupō Unrest Scenario (TUS) was developed in August 2019 as a product of the ECLIPSE Scenario Framework. This section details how and why the TUS was developed, including what case studies that were used to inform the phenomena illustrated within the scenario.

4.1.1 Taupō Unrest Scenario Characterisation

Caldera volcano unrest phenomena commonly includes seismicity, ground deformation and changes in the geothermal and hydrothermal systems (Potter, Scott & Jolly, 2012). These phenomena can be potentially hazardous and can result in psychosocial and economic impacts, all of which have occurred in the past 160 years at the Taupō Volcanic Centre (TaVC), and overseas (Potter, Scott & Jolly, 2012).

The importance of developing a scenario that consisted of caldera unrest, whether or not it lead to eruption, was also identified in the ECLIPSE Scenario Development Workshop (ESDW) in March 2019 (*Chapter 3; Appendix B*). CDEM Groups emphasised the importance of acknowledging and developing unrest impacts as part of the ECLIPSE Scenario Framework research, particularly impacts where physical hazards, such as ground deformation, cause multiple secondary impacts, such as economic, psychosocial, and impacts on infrastructure. Industry and Lifelines representatives complemented this, suggesting that a wide range of scenarios would be useful, specifically listing unrest, and that it would be important to involve the multi-hazard aspect in these scenarios. GeoNet representatives further emphasised development of unrest scenarios, stating, in response to the exemplar scenario shown during the workshop (*Appendix B*), that including more unrest science would be beneficial and was missing from the exemplar. CDEM Groups, Iwi and Industry stakeholders also identified that the type of unrest would also have significant influence on their decision-making and actions, stating that the temporal aspect of unrest would be crucial to understanding and informing risk management (i.e. rapid-onset activity would drive different priorities than a relatively "slower", more prolonged unrest period).

Four significant episodes of caldera unrest have occurred historically in the TaVC (*Table 4.1*) and further research has indicated that many more episodes have occurred in between these (Potter, Scott & Jolly, 2012; Potter et al., 2015ab). These episodes range from minor unrest to months of earthquake swarm, resulting in significant social and economic implications and, based on the frequency of unrest in the TaVC, it is likely that this activity will occur in future (Potter, Scott & Jolly, 2012). Research in the TaVC (Potter, Scott & Jolly, 2012; Potter et al., 2015ab) has further indicated that the phenomena from past episodes will almost certainly be repeated in future, at varying intensities, and therefore, two of these unrest episodes (1922 and 1983) have been used to model some of the TUS behaviour.

Table 4.1: Defined unrest episodes from the TaVC in the central TVZ (Potter, Scott & Jolly, 2012; Newhall & Dzurisin, 1988; Webb, Ferries & Harris, 1986).

DATE OF UNREST EPISODE	GEOLOGIC PHENOMENA	IMPACTS AND IMPLICATIONS
17th August – September 1895	M_w6-7.5 earthquake causing hundreds of landslides, some large, blocking roads around Lake Taupō. Six weeks of aftershocks	Collapsed chimneys and contents damage in Taupō township. Minor injuries. Psychological impacts. Self-evacuations. Effects on tourism.
April 1922 – January 1923	Earthquakes migrated north to south through Taupō district over six months. Landslides blocking roads. ~1m of uplift, followed by 3.7m of subsidence in the northern part of Lake Taupō.	Several collapsed chimneys, contents damage. Psychological impacts. Evacuations. Impact on tourism in Taupō and Rotorua due to incorrect international reporting.

	Minor changes to hot springs and geysers' activity. Fissuring and faulting.	Caused liquefaction and water "fountains" emerging from ground cracks, causing flooding.
December 1964 – January 1965	Up to 1,125 earthquakes over the two months. Potential tremor observed. <160mm of possible uplift.	Cracks in buildings, chimneys moved, crockery broke. Rumours around unrest. Perceived impact on tourism of "exaggerated" reports.
February – March 1983 **March – June 1983** **16th June 1983** **23rd June 1983** **29th-30th June 1983**	Earthquake swarms northwest of Lake Taupō. <30 tremors recorded per day. Northern Lake Taupō shore uplift of 5.7cm. New, stronger earthquake swarm (<M_w4.3). Kaiapo Fault ruptured. Earthquake swarms.	Rapid subsidence experienced northwest of Kaiapo Fault. Minor damage reported, including cracked chimneys and fallen ornaments.

As unrest episodes usually do not leave any trace in the geological record, they are limited to areas of human occupation and written records, as a result, A-NZ's record is reasonably limited (Potter, Scott & Jolly, 2012). However, there are a number of overseas caldera volcanoes that are similar to those in the central TVZ, such as Campi Flegrei (Italy), Yellowstone (USA), Chaitén (Chile), and Rabaul (Papua New Guinea), and therefore can be used for modelling unrest behaviour. For the TUS, the 1970s-1980s unrest at Rabaul caldera was used to complement the 1922 and 1983 TVC episodes, outlined below.

The combination of caldera unrest literature, both global and local, and qualitative data from the ESDW therefore provided a sound evidence base for and drove the development of ECLIPSE Scenario A: Taupō Unrest Scenario.

4.1.2 Taupō Unrest Scenario Development

This section outlines how ECLIPSE Scenario A was developed, while the scenario itself is outlined in *Section 4.1.3* below.

The location of the TUS was determined based on local history, which infers that a future vent will most likely be within Lake Taupō, near the Horomatangi Reefs or Motutaiko Island, near the most recently active vents (*Figure 4.1.1*) (Froggatt, 1997; Potter, Scott & Jolly, 2012).

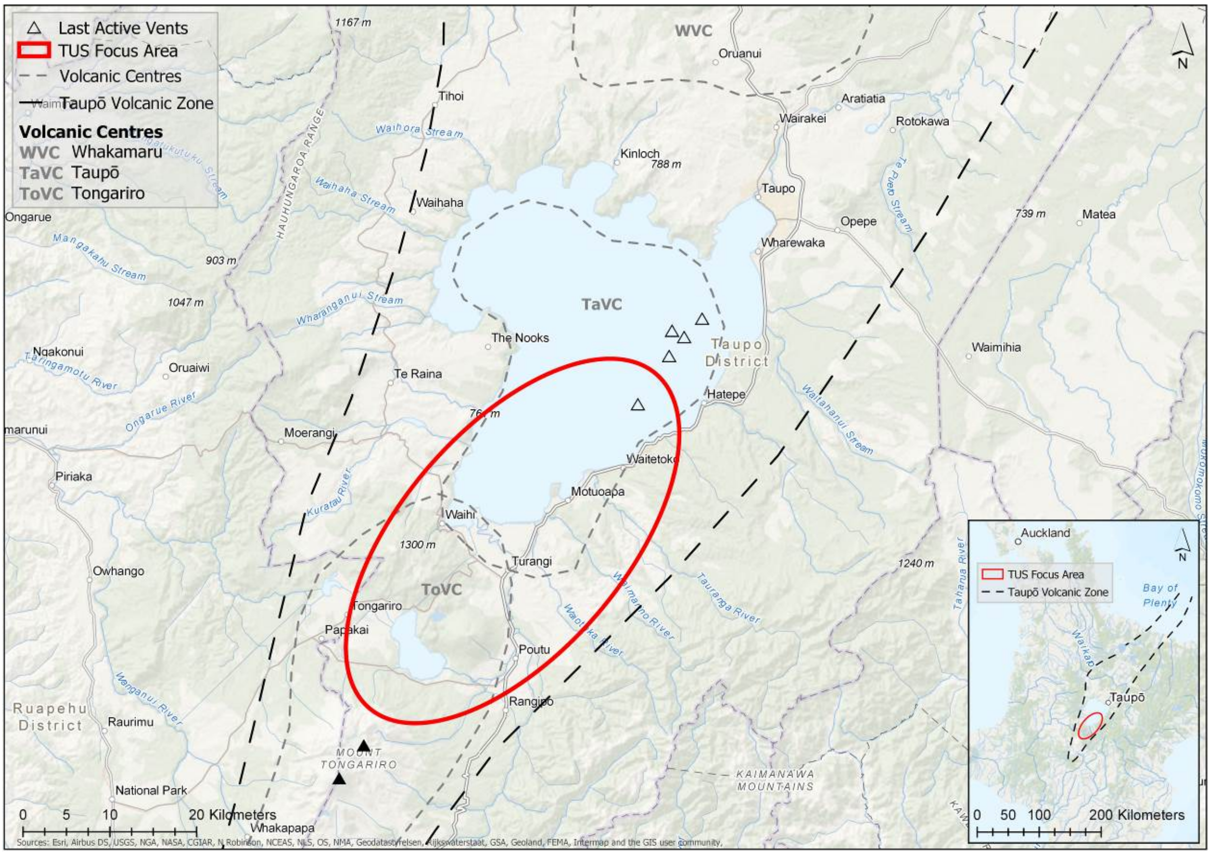

Figure 4.1.1: Area of the TUS developed from the ECLIPSE Scenario Framework.

The Okataina Volcanic Centre (OVC) earthquake event in July 2004 (*Appendix F.3*) and the unrest episode at the TaVC in 1922 (*Appendix F.1*) were used to inform the initial earthquake and its direct consequences for the TUS. The initial earthquake and four substantial aftershocks were directly modelled from the 2004 OVC event, with landslides modelled from both the 2004 and 1922 events. The seiching on lake shores and liquefaction in Waimarino Swamp at Stump Bay, as a result of the earthquake, were informed by expert advice within the research team.

The earthquake swarms, starting in late 2019 and continuing throughout the TUS, were mirrored from the 1983 TVC (*Appendix F.1*) unrest and the Rabaul 1970-1980s (*Appendix F.2*) unrest episodes (taking the data and superimposing it onto the modern day area). The locations and spatial patterns of the swarms were taken from the 1983 TaVC events, however, in an opposite direction. The frequency over time and relative intensity pattern of the swarms were informed from the Rabaul unrest episode.

The ground deformation within the TUS was modelled from both the 1922 and 1982 TaVC events, as well as the Rabaul unrest episode. The locations of ground deformation occurrence in the TUS was mirrored specifically from the TaVC unrest events, while the quantity, intensity and change through time was derived from Rabaul. The geothermal changes throughout the TUS were also modelled from the 1922 TaVC event.

Finally, the change in the Volcanic Alert Level (VAL), from Level 0 to Level 1 was informed by expert advice from within research team and literature, which stated that if the VAL had existed during previous TaVC unrest episodes, the events may have been assigned a level of VAL 1 or even VAL 2 (Potter, Scott & Jolly, 2012). The social impacts, public anxiety and voluntary evacuations, were also informed by the impacts experienced in the 1922 TaVC event.

4.1.3 Taupō Unrest Scenario

ECLIPSE Scenario A: the Taupō Unrest Scenario (TUS) is a four and a half year long unrest scenario located within the TaVC (*Figure 4.1.2; Table 4.2*). The scenario begins with a M_w5.4 earthquake occurring to the southeast of Turangi at 10km depth (*Figure 4.1.1; Figure 4.1.4*). The scenario then progresses through several hazards and impact suggestions resulting from the earthquake event that begin to indicate more than just tectonic behaviour. Scenario A concludes in open-ended fashion (*Figure 4.1.3*), allowing stakeholders several options on where to go next, such as leaving the scenario exercise there or choosing to have the behaviour lead onto an eruption. The impacts from the physical phenomena are indicative only and should be developed further from this project. The impacts are underdeveloped in comparison to the physical phenomena as they require an in-depth analysis themselves, which was out of scope for this project, and subject matter experts' (and stakeholder) input to guide their development, which was also out of scope for this project (this also applies for the impacts developed as part of ECLIPSE Scenario B, *Section 4.1*).

Table 4.2: ECLIPSE Scenario A: Taupō Unrest Scenario timeline in table form. The "Map" column relates to Figures 4.1.4 to 4.1.9 below which map the hazards occurring throughout the scenario.

YEAR	MONTH	DATE	OBSERVATIONS	IMPACTS	MAP
2019	JUL	1st 20th	Earthquake swarm. M_w5.4 earthquake. 10km depth on Poutu Fault. Landslides reported around earthquake's epicentre. Liquefaction in Waimarino Swamp at Stump Bay.	Causes damage to State Highway 1 (SH1) near Stump Bay and the Hipaua Steaming Cliffs.	Y1a

		29th	Earthquake swarm.		
	AUG	3rd	Strongly felt M_w4.1 aftershock occurs.	Causes damage to SH1 along the Tongariro River.	Y1b
	SEP	12th	Strongly felt M_w3.9 aftershock occurs.	More damage.	Y1b
	OCT	16th	Strongly felt M_w3.1 aftershock occurs.	Public concern increased.	Y1b
		19th	Earthquake swarm at southern end of Lake Taupō (<M_w2.5).		
	NOV	19th	Motuoapa Springs increase in temperature.		Y1b
		24th	Significant M_w3.0 aftershock occurs.		
	DEC	10th	Earthquake swarms continue (<M_w2.0-2.5).		Y1b
2020			Earthquake swarms continue throughout year (<M_w2.0-2.5).	Self-evacuation of hundreds of people.	Y2
	FEB		~3cm of uplift recorded on eastern Lake Taupō shore.		Y2
	JUN		~1cm of uplift recorded on north-eastern Lake Taupō shore.		Y2
	NOV		Motuoapa Hot Springs increase in temperature.	Significant numbers of people start to return.	Y2
2021	JAN		Earthquake swarms continue throughout year (<M_w2.0-2.5) with an increase in the number of earthquakes per swarm.	Volcanic Alert Level (VAL) raised to Level 1 (VAL1).	Y3
					Y3
	FEB		~10cm of uplift recorded on north-eastern Lake Taupō shore.		Y3
					Y3
	JUN			Wide public anxiety. Some people starting to leave areas surrounding Lake Taupō.	Y3
	OCT		~7cm of uplift recorded on the eastern Lake Taupō shore.		
	DEC		Horomatangi geothermal system increases in activity.		
2022	JAN		Earthquake swarms continue throughout year with an increase in magnitude to M_w2.5-3.0.		Y4
					Y4
	MAR				

	JUL NOV	~1cm of uplift recorded on the eastern Lake Taupō shore. ~3cm of uplift recorded on the north-eastern Lake Taupō shore. Horomatangi geothermal systems increases in temperature.		Y4 Y4
2023	JAN APR MAY SEP	Earthquake swarms continue through first quarter of the year with an increase in magnitude to M_w3.0-3.5. ~10cm of uplift recorded on the eastern Lake Taupō shore. Earthquake swarms continue throughout later part of year with an increase in magnitude to M_w3.5-3.9. Some individual earthquakes are recorded at M_w4.0. Horomatangi geothermal system increases in activity.	Hundreds of people begin to leave the area again.	Y5 Y5 Y5 Y5

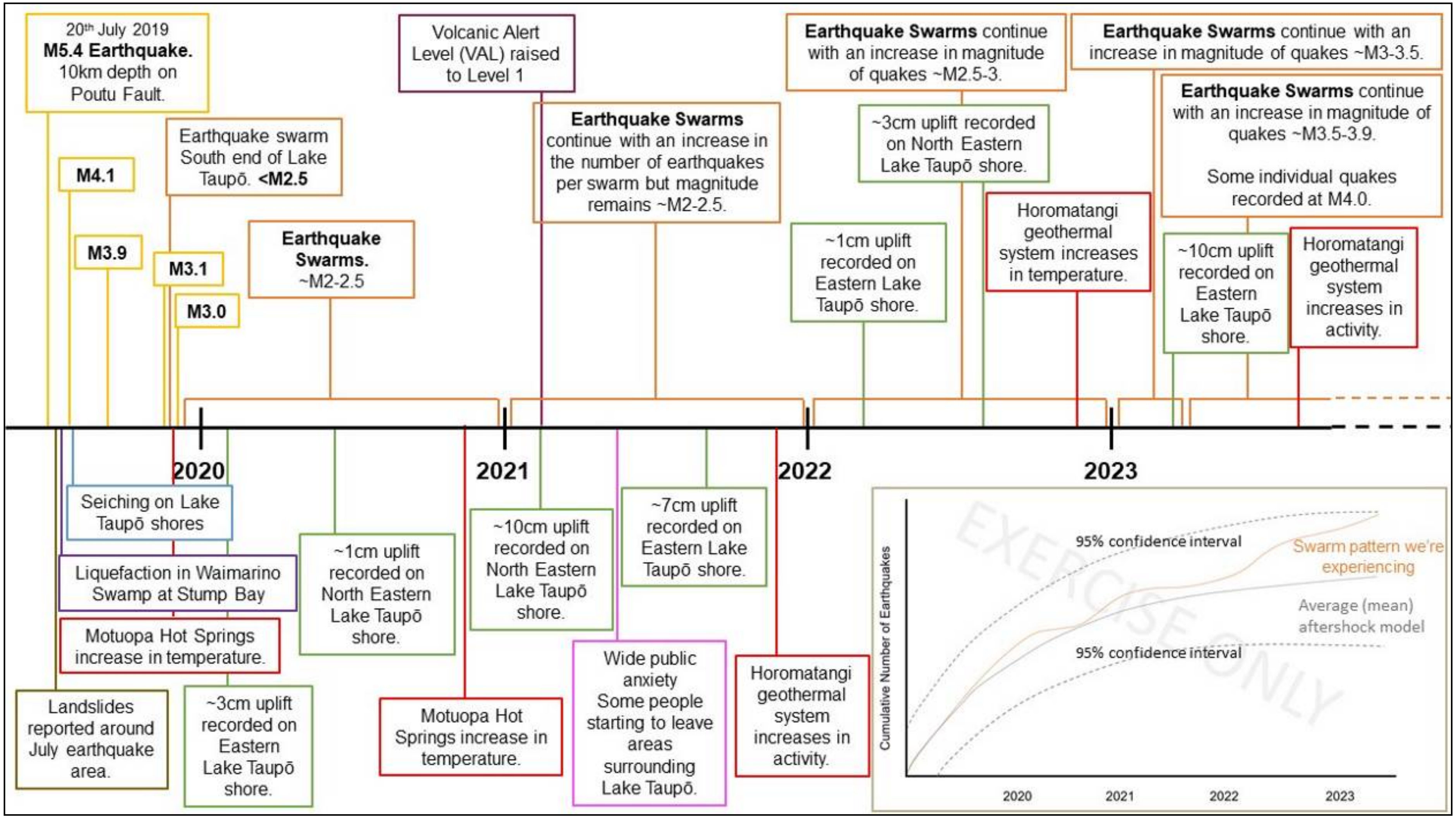

Figure 4.1.2: ECLIPSE Scenario A: Taupō Unrest Scenario visual timeline of events.

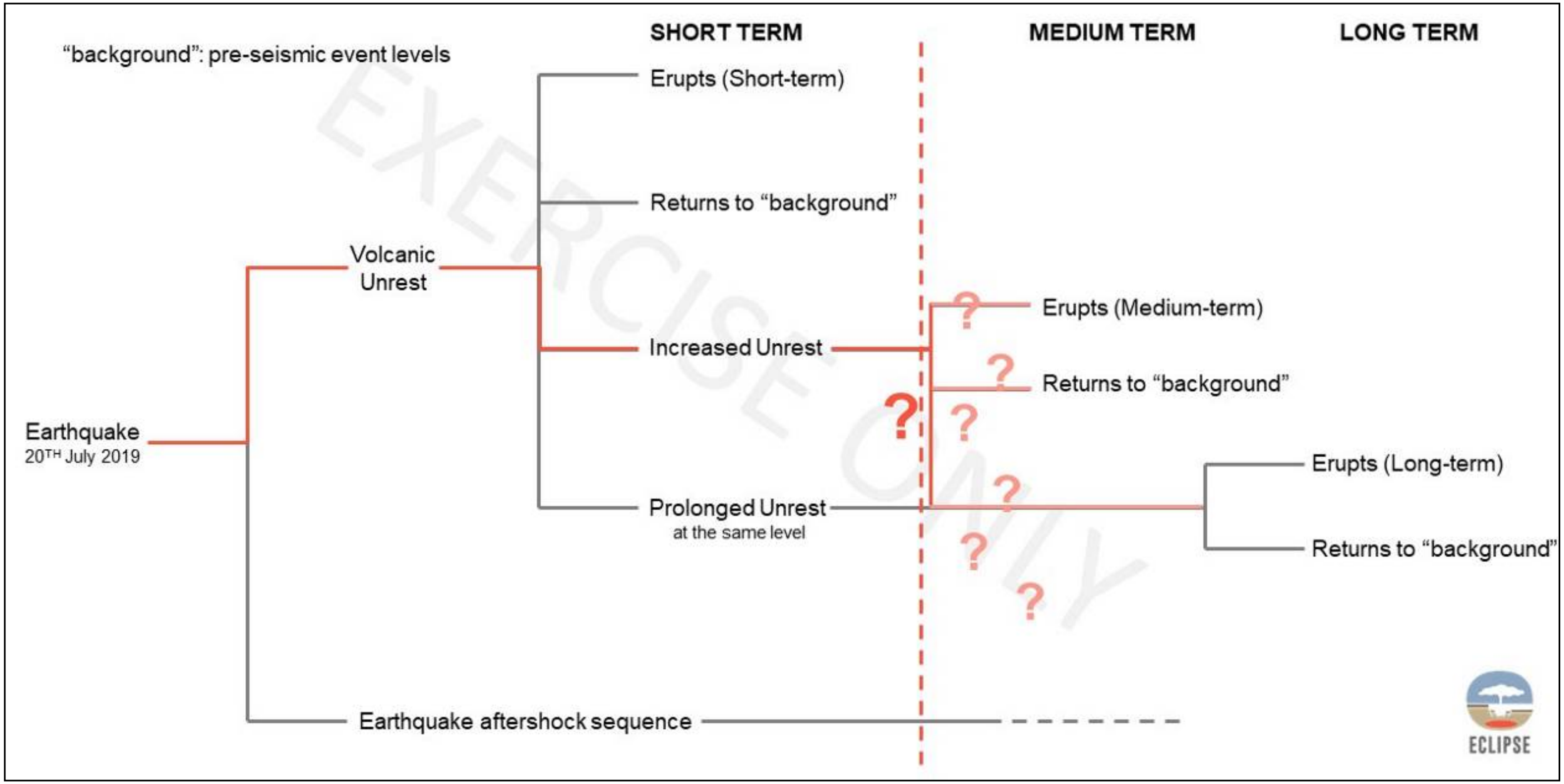

Figure 4.1.3: ECLIPSE Scenario A: Taupō Unrest Scenario logic-tree depicting the uncertainty of what happens next (which can ultimately be decided by the end-user through further development of the scenario).

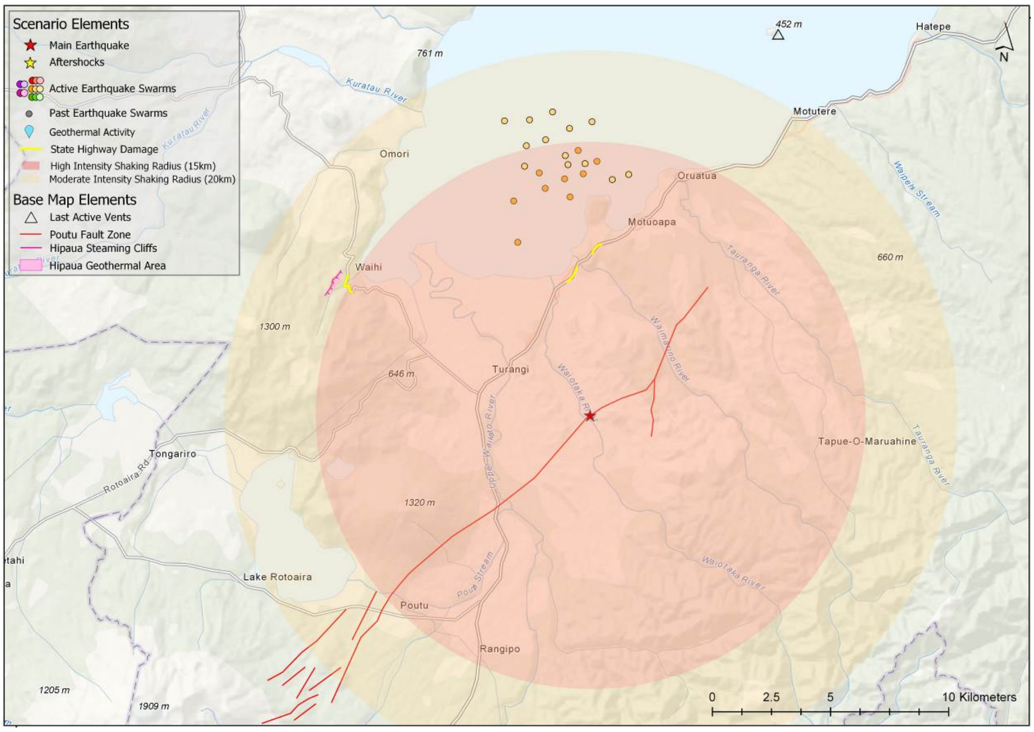

*Figure 4.1.4: **Map Y1a:** Depicting phenomena experienced in July of 2019. The dark orange filled dots represent the earthquake swarm on July 1st 2019, while the lighter orange filled dots represent the earthquake swarm on 29th July 2019.*

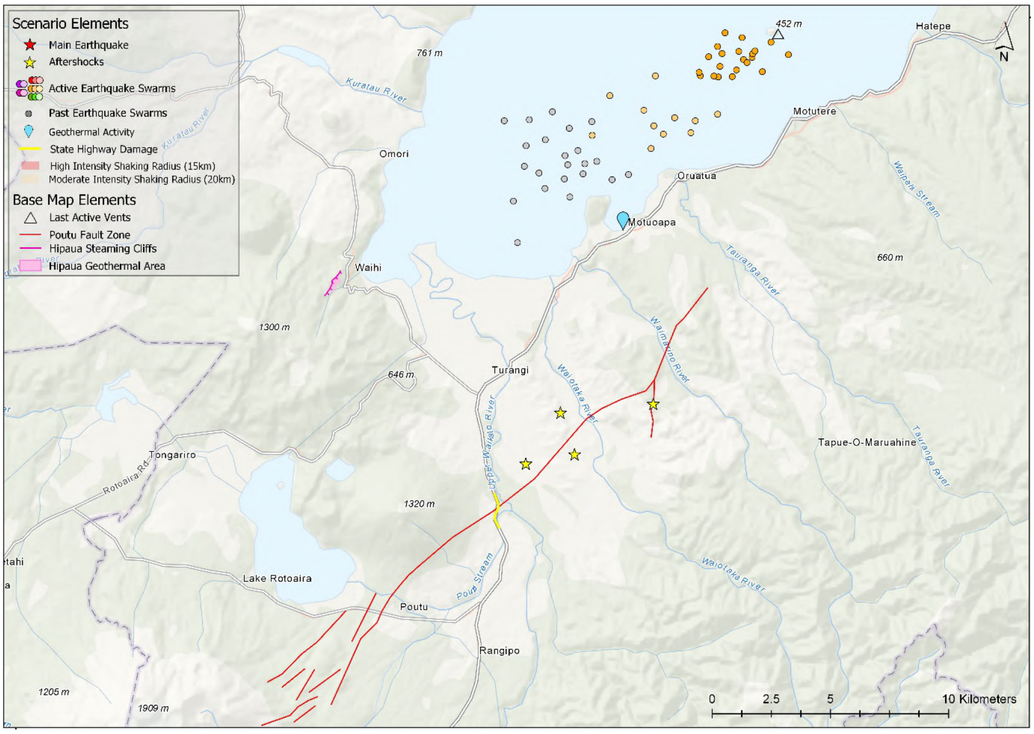

*Figure 4.1.5: **Map Y1b:** Depicting phenomena experienced from August 2019 to December 2019, with past earthquake swarms in grey tones to illustrate the direction of swarm migration. The light orange dots represent the earthquake swarm on 19th October 2019, while the dark orange dots represent the earthquake swarm on 10th December 2019. The M_W4.1 aftershock on 3rd August 2019 is represented by the very western yellow star (next to*

State Highway 1), with the 16th October 2019 aftershock the very northern star, the 24th November 2019 aftershock the very eastern star, and the 12th September 2019 aftershock the western, middle star.

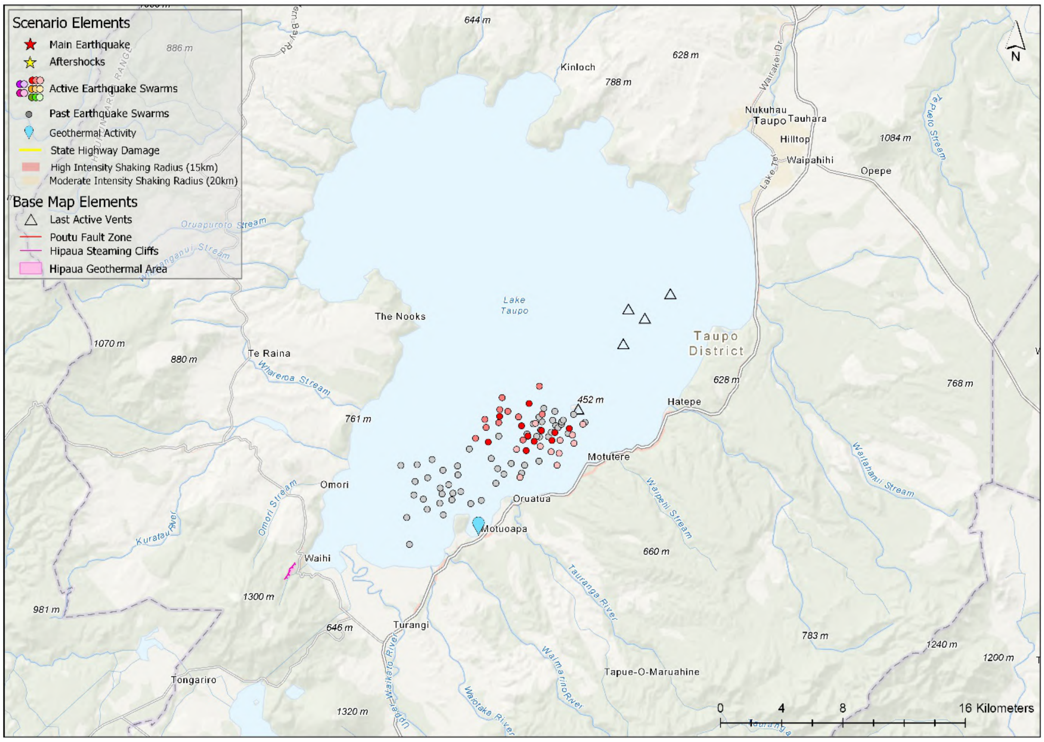

Figure 4.1.6: ***Map Y2:*** *Depicting phenomena experienced throughout 2020, with past earthquake swarms in grey tones to illustrate the direction of swarm migration.*

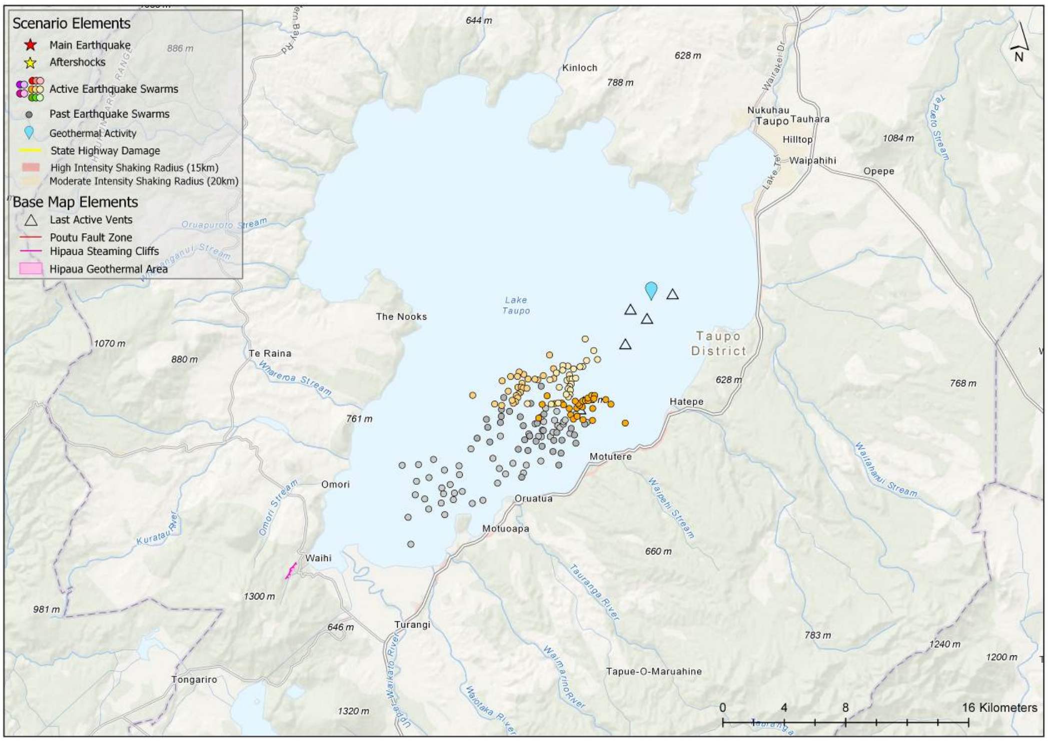

Figure 4.1.7: ***Map Y3:*** *Depicting phenomena experienced throughout 2021, with past earthquake swarms in grey tones to illustrate the direction of swarm migration.*

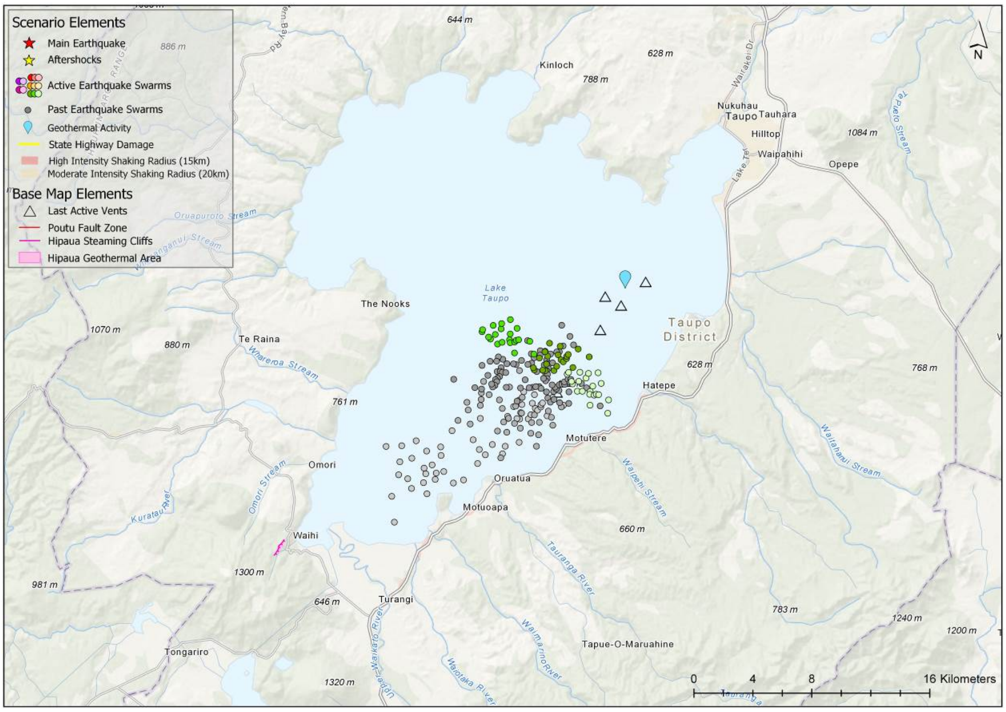

*Figure 4.1.8: **Map Y4:** Depicting phenomena experienced throughout 2022, with past earthquake swarms in grey tones to illustrate the direction of swarm migration.*

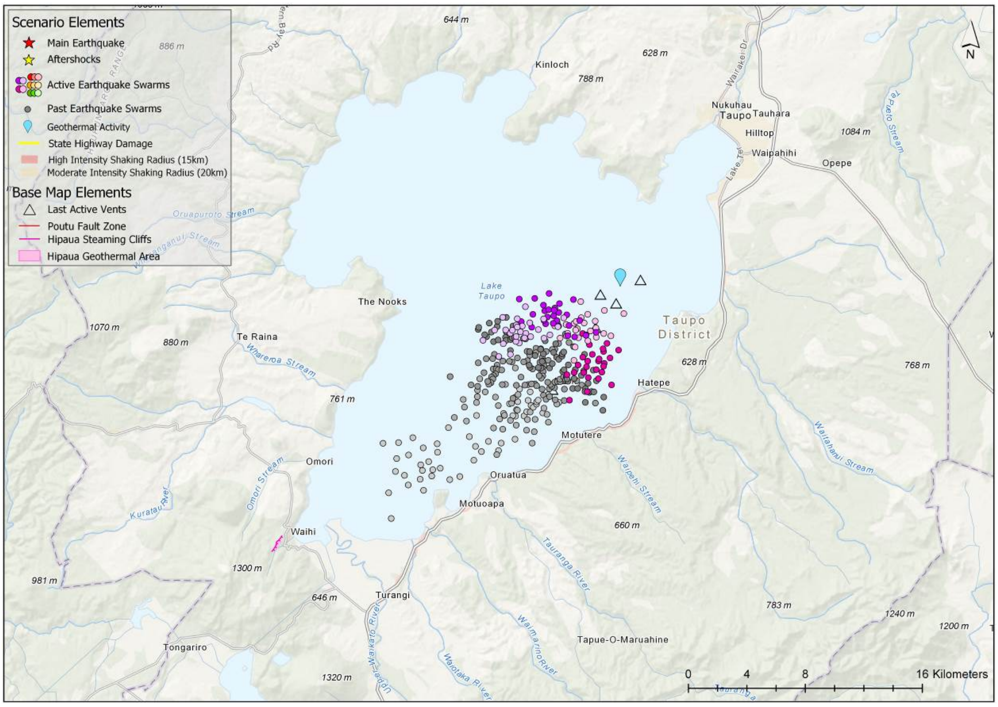

*Figure 4.1.9: **Map Y5:** Depicting phenomena experienced throughout 2023, with past earthquake swarms in grey tones to illustrate the direction of swarm migration.*

4.2 ECLIPSE Scenario B: Taupō Eruption Scenario

ECLIPSE Scenario B: Taupō Eruption Scenario (TES) was developed in October 2019 as a product of the ECLIPSE Scenario Framework. This section details how and why the TES was developed, including what case studies that were used to inform the phenomena illustrated within the scenario.

4.2.1 Taupō Eruption Scenario Characterisation

The TaVC has been the source of a range of eruption sizes, from small explosions to super-eruptions, that occur relatively infrequently in comparison to other silicic centres, such as the OVC (Wilson, et al., 1984). These eruption events commonly include phenomena such as seismicity, ash fall, pyroclastic flows, and mudflows, amongst many other potential hazards (Potter, Scott & Jolly, 2012; Manville, Hodgson & Nairn, 2007; GNS Science, 2010c).

The importance of developing a scenario consisting of a substantial sized eruption, with far-reaching impacts, was identified in the ECLIPSE Scenario Development Workshop (ESDW) in March 2019 (*Chapter 3; Appendix B*), where stakeholders identified that having a scenario that crossed multiple regions would be useful to help build preparedness and to challenge planning. More specifically, stakeholders emphasised the importance of including commonly overlooked hazards, such as ground deformation and earthquakes, alongside built and societal environment impacts, such as societal behaviour. CDEM Groups identified that impacts should be present throughout the scenario, linked to each phase of volcanic behaviour and that cues as to what other organisations were doing, such as GeoNet (via VALs), would be useful for informing their responses. GeoNet representatives further emphasised this by suggesting that the inclusion of VALs would improve the similarity of the scenario to reality. Furthermore, GeoNet and Iwi representatives identified that timescales of the volcanic phenomena, with duration of each hazard and phase, would be beneficial. Overall, stakeholders identified that it was important that both the hazards and impacts were detailed and provided enough information to understand what was happening and form responses and actions based off the events within the scenario.

The combination of caldera eruption literature, detailed in *Chapter 1*, and the qualitative data from the ESDW therefore provided justification for and drove the development of ECLIPSE Scenario B: Taupō Eruption Scenario.

4.2.2 Taupō Eruption Scenario Development

This section outlines how ECLIPSE Scenario B was developed, while the scenario itself is outlined in *Section 4.2.3* below.

The location of the TES was determined based on local history, which states a future vent will most likely be within Lake Taupō, near the Horomatangi Reefs or Motutaiko Island (Froggatt, 1997; Potter, Scott & Jolly, 2012). The location was further derived from the proximity to the vent that erupted during the 186 AD eruption (*Figure 4.2.9*) (Wilson & Walker, 1985a).

The earthquake swarms, starting in January 2022 and continuing through until eruption, were mirrored from the 1983 TaVC unrest and the Rabaul 1970s-1980s unrest episodes (*Appendices F.1* and *F.2*). The locations and spatial patterns of the swarms were superimposed from the 1983 TVC events, with the frequency over time and relative intensities of the swarms informed from the Rabaul unrest episode.

The ground deformation within the TES was derived from both the 1922 and 1983 TaVC events, as well as the Rabaul unrest episode. The locations of ground deformation were derived specifically from the TaVC unrest events, while the quantity, intensity and change through time was derived from Rabaul. The geothermal changes throughout the TES were also modelled from the 1922 TaVC event.

The eruption phenomena throughout the TES were informed from the 186 AD eruption event (*Appendix F.1*). The ash fall (isopachs; eruption phases one to three and five to six) were derived from Walker (1980; 1981ab) and Wilson & Walker's (1985a) previous research, and coupled with an understanding of the predominant wind directions over A-NZ's central North Island (Wilson et al., 2009). The "waterspouting" (water falling from the eruption column), in phase four of the eruption, was derived from descriptions by Wilson & Walker (1985a), who drew similarities to "waterspouting" that occurred during the 1937 eruption event at Rabaul caldera. The early pyroclastic flows, extending to the north and northeast of the vent, and the more widespread pyroclastic flow in the later part of phase six of the eruption were also derived from Wilson & Walker's (1985ab) research.

The post-eruption phenomena in the TES were also informed from the 186 AD eruption event, with the assumption that all rivers linking to the pyroclastic flow deposit from phase six would in some way or another present a mudflow (lahar) hazard (Wilson & Walker, 1985a). Previous research in the Taupō district had also identified that a catastrophic flood occurred post-186 AD eruption and would therefore, likely occur again. This catastrophic flood resulted from a dam-break, where the outlet from Lake Taupō to the Waikato River had been dammed with pyroclastic material as a result of the eruption and, after re-filling over several decades, the lake level eventually overtopped the dam, sending 20km^3 of water downstream in a single phase (Manville et al., 1999; Manville, 2002; Manville, Hodgson & Nairn, 2007). These lahar and river flooding events would likely occur for decades after the eruption, however, the scenario only details short-term post-eruption due to time constraints for development time for the scenario.

The changes in the VALs throughout the scenario were informed by a combination of expert advice from within the research team, literature (Potter, Scott & Jolly, 2012; Potter et al., 2015ab), and what has occurred previously in response to volcanic eruptions at A-NZ's volcanoes. The social impacts, public anxiety and voluntary evacuations, were also partially informed by the impacts experienced in the 1922 TaVC event and the Rabaul unrest episode.

4.2.3 Taupō Eruption Scenario

ECLIPSE Scenario B: Taupō Eruption Scenario (TES) is a two year unrest to eruption scenario located within the TaVC (*Figure 4.2.1; Table 4.3*). The scenario begins with already present unrest causing the VAL to be at Level 1 (*Figure 4.2.1*). The scenario then progresses through several phases of unrest (*Figures 4.2.2 to 4.2.*8) before it eventually begins to erupt. It follows through the eruption, six phases of eruptive behaviour (*Figures 4.2.9 to 4.2.16*), before ceasing eruption. Scenario B ends indicating that long-term hazards are likely to continue occurring for some time after the scenario ends (*Figures 4.2.17 and 4.2.18*).

Table 4.3: ECLIPSE Scenario B: Taupō Eruption Scenario timeline in table form. The "Map" column relates to Figures 4.2.2 to 4.2.18 below which map the hazards occurring throughout the scenario.

YEAR	MONTH	TIME	OBSERVATIONS	IMPACTS	MAP
2022	JAN		Earthquake swarms of ~Mw2.5 – 3 occur underneath Lake Taupō.		U1
	MAR		~1cm uplift recorded on eastern Lake Taupō shore.		U1
	JUL		~3cm uplift recorded on north-eastern Lake Taupō shore.		U2
	OCT		Horomatangi geothermal system increases in temperature.		U3
2023	JAN		Earthquake swarms of ~Mw3 – 3.5 occur underneath Lake Taupō.		U4
	MAR		~10cm uplift recorded on eastern Lake Taupō shore.		U4
	APR		Earthquake swarms increase to ~Mw3.5 – 3.9 with some individual earthquakes recorded at Mw4.		U5
	AUG		Horomatangi geothermal system increases in activity.	Hundreds of people begin to leave the area again.	U6
	SEPT		An increase in the frequency of Mw4 earthquakes and earthquake swarms.		U7
	OCT		Horomatangi geothermal system rapidly increases in activity.		U7
	6th NOV	1500	Phreatomagmatic eruption occurs with the vent below the water's surface. Eruption column – 10km high. South-westerly winds present.		E1
		2300	Plinian eruption occurs with the vent above the water's surface. Eruption behaves as a continuous gas blast with minor fluctuations throughout sustained activity. Eruption column – 30km high. Local south-westerly winds, with high level west-south-westerly winds.	Ash reaches Taupō township – eventually carried as far as the East Coast.	E2
	8th NOV	0000	A sudden increase in water (from the lake) into the vent causes the Plinian eruption column to interact with water. Water falls alongside ash.	Ash eventually reaches the East Coast.	E3
		2000	Water-spouting occurs – water falling from the eruption column extensively gullies the already deposited ash blanket.		E4
	9th NOV	0400	Ash emissions cease.		

	30th NOV	1400	Plinian eruption occurs with a 30km high eruption column. Interaction with water continues and so ash falls at wet, cohesive mud.		E5
	1st DEC	1000	Largest Plinian eruption yet occurs with 38km high eruption column. Slumping of ground (caused by ground shaking) is experienced in Taupō township.		E6a
		1600	Pyroclastic flows are generated (reducing eruption column height) and extend in eastern, north-eastern and northern directions.	Taupō township is covered with pyroclastic material.	E6b
	2nd DEC	0300	Eruption climax produces a single, massive pyroclastic flow that spreads in all directions from the vent's location in Lake Taupō in a matter of minutes.	Area within 80km of Lake Taupō (radially) covered in a blanket of pyroclastic material.	E6c
2023 – 2024	Hours to months post-eruption		Explosions consisting of gas and deposited material occur sporadically.		
			Mudflows travel for tens of hundreds of kilometres (eventually reaching the East Coast). Ground shaking continues as the area degases.	Travelling down rivers surrounding the Lake Taupō area and stretch to both the east and west coasts.	PE1
2024 onwards	Months to decades post-eruption		Further mudflows. Dam-break flooding from Lake Taupō if eruptive products block Lake outlets.	Travels down the Waikato River.	PE2

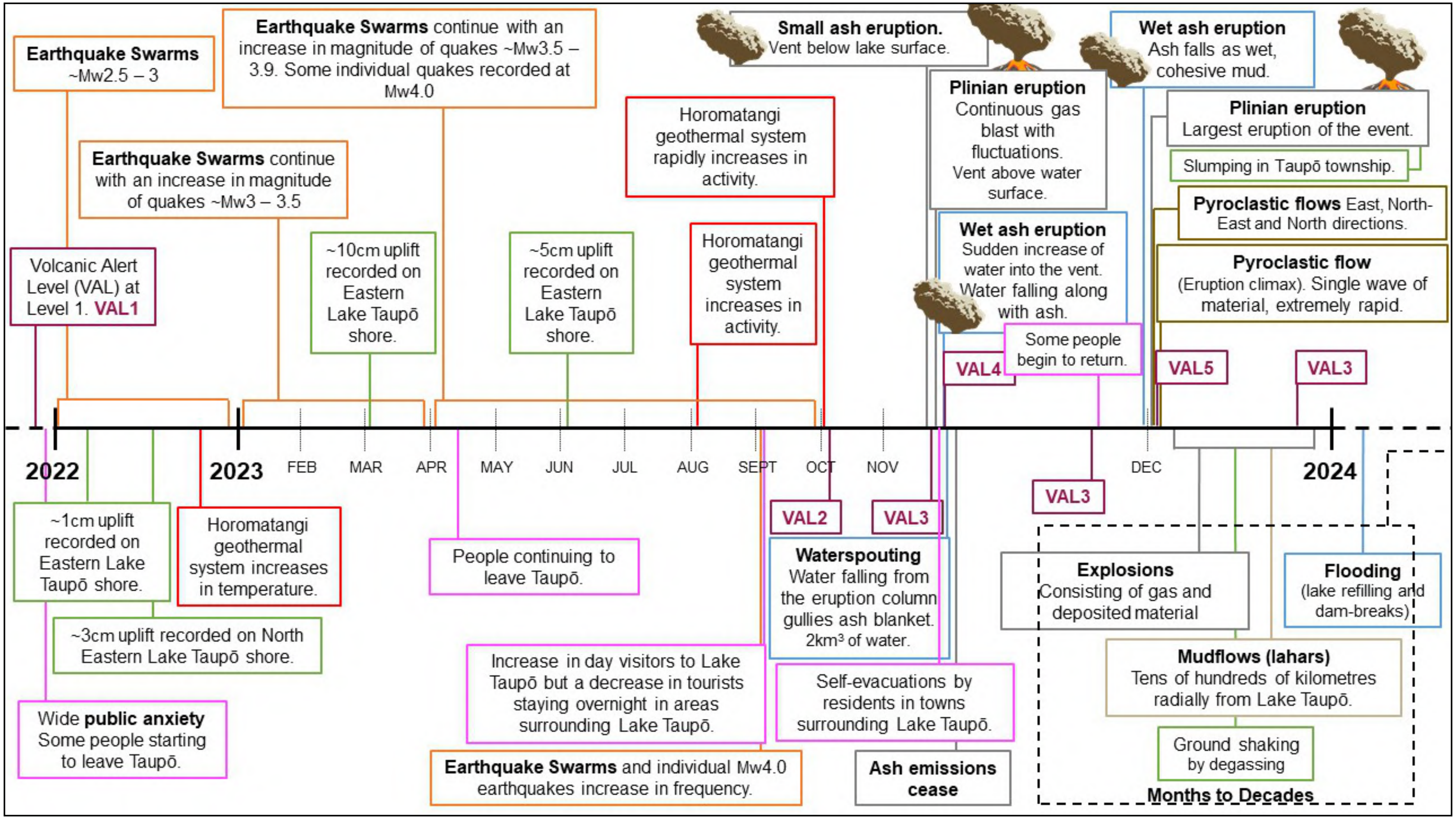

Figure 4.2.1: ECLIPSE Scenario B: Taupō Eruption Scenario visual timeline of events.

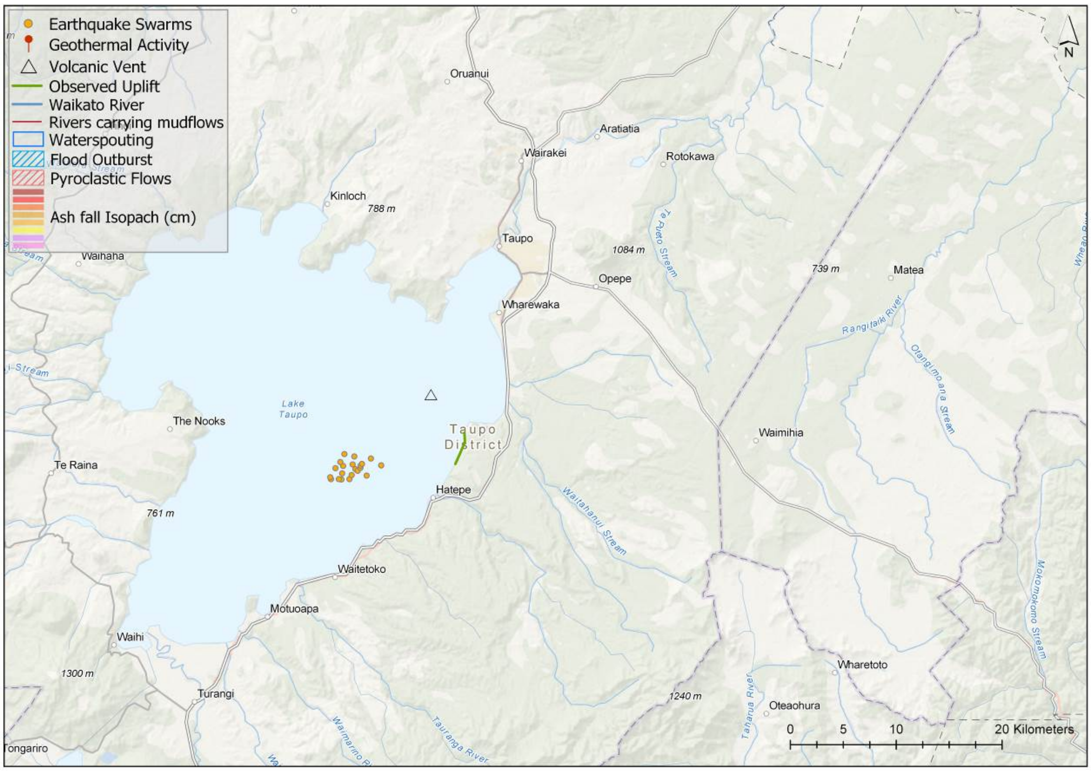

Figure 4.2.2: ***Map U1:*** *Depicting phenomena experienced in January and March of 2022.*

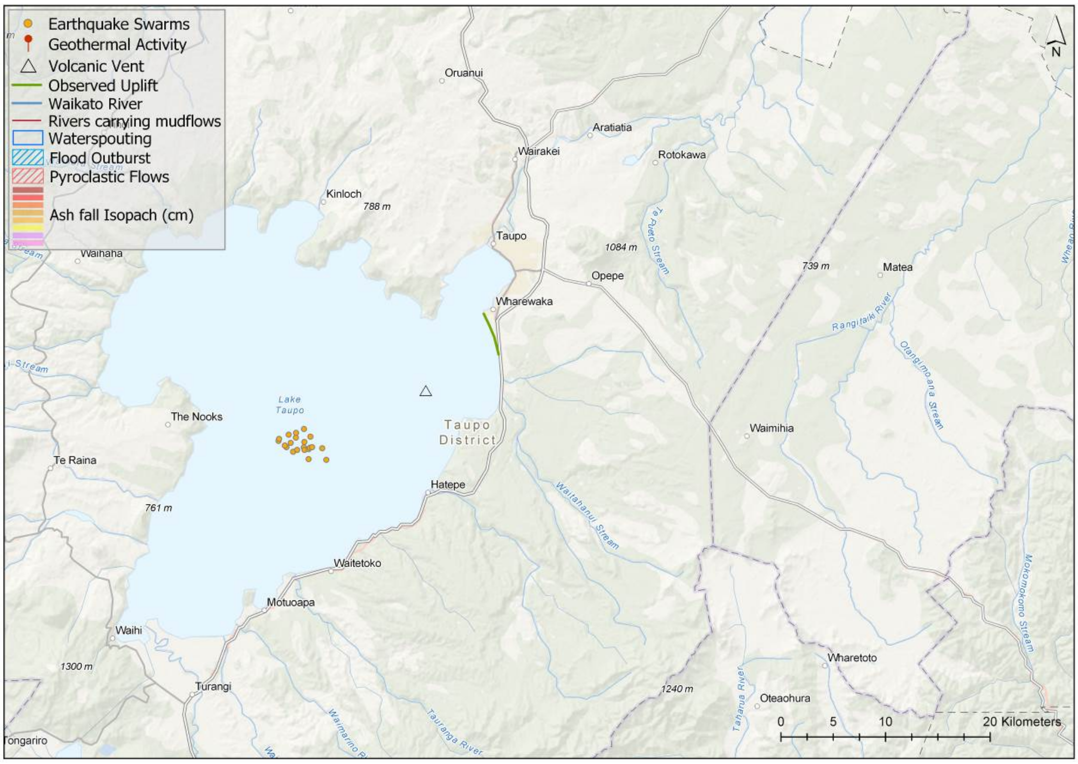

Figure 4.2.3: ***Map U2:*** *Depicting phenomena experienced in July of 2022.*

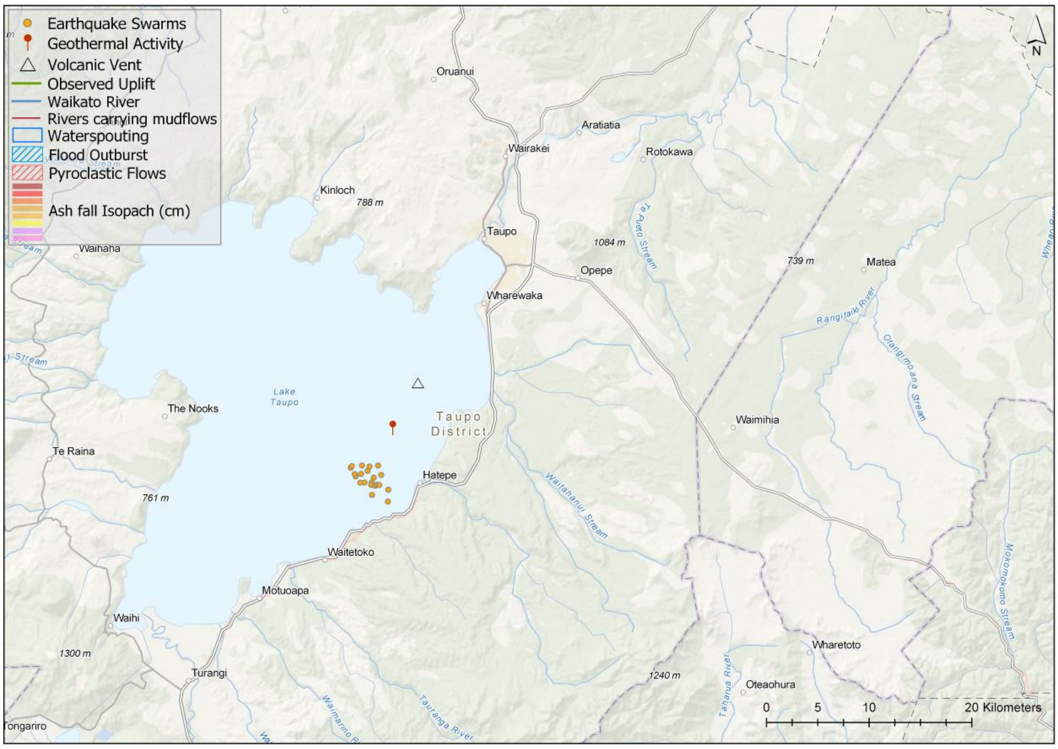

*Figure 4.2.4: **Map U3:** Depicting phenomena experienced in October of 2022.*

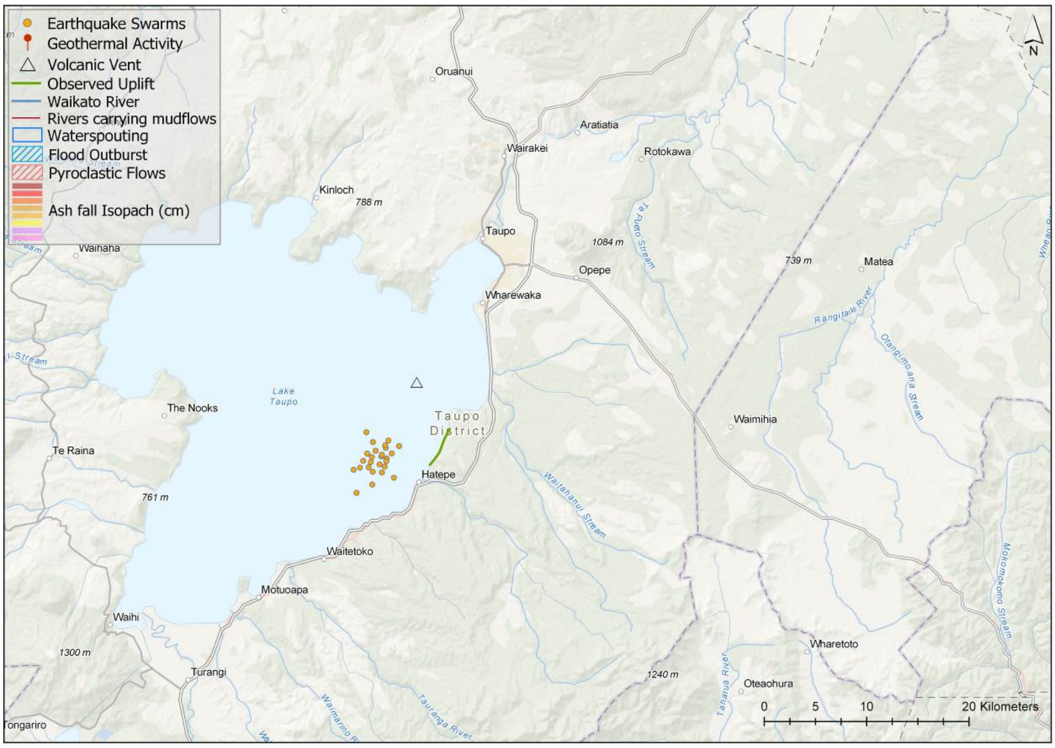

*Figure 4.2.5: **Map U4**: Depicting phenomena experienced in January and March of 2023.*

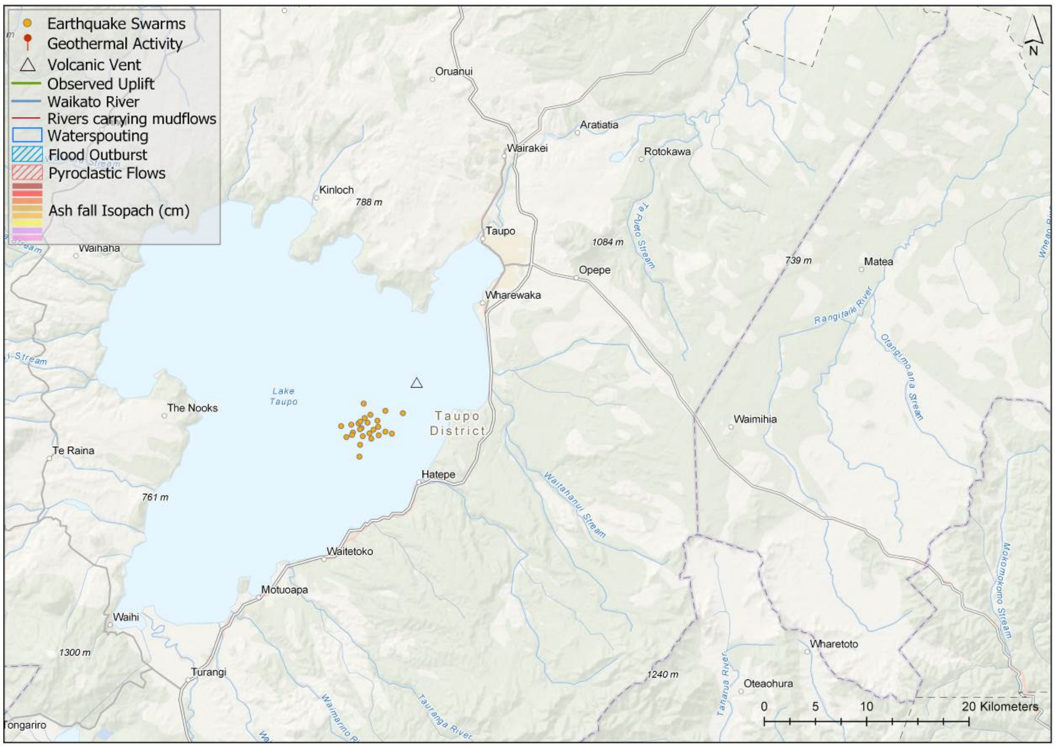

*Figure 4.2.6: **Map U5:** Depicting phenomena experienced in April of 2023.*

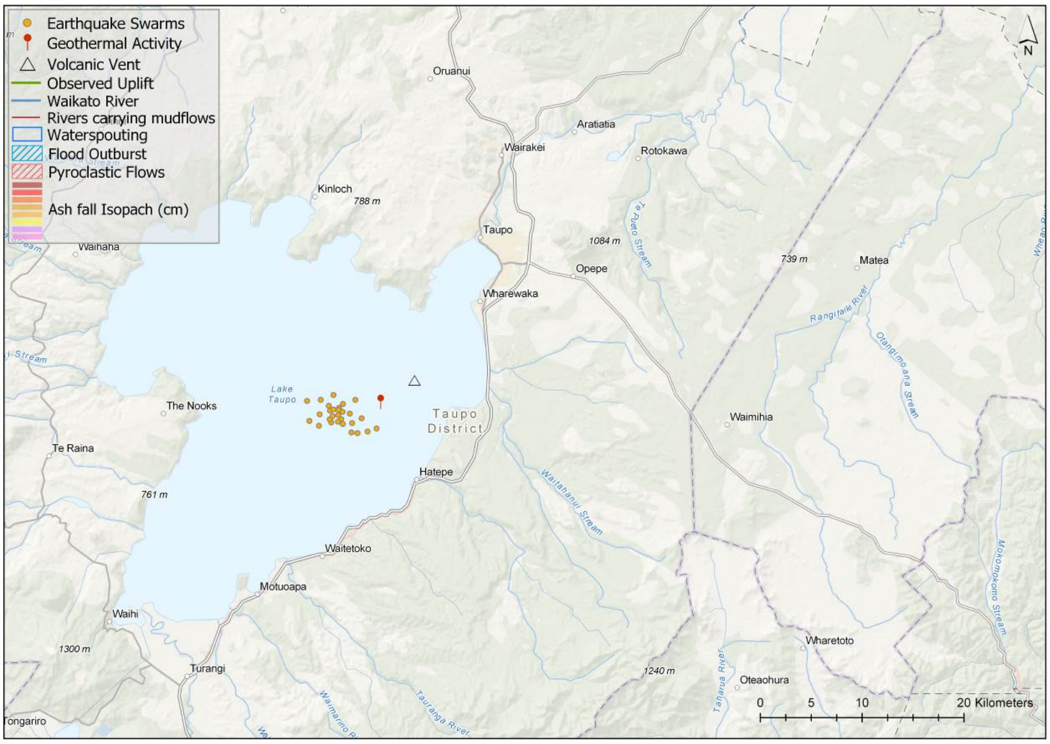

*Figure 4.2.7: **Map U6:** Depicting phenomena experienced in August of 2023.*

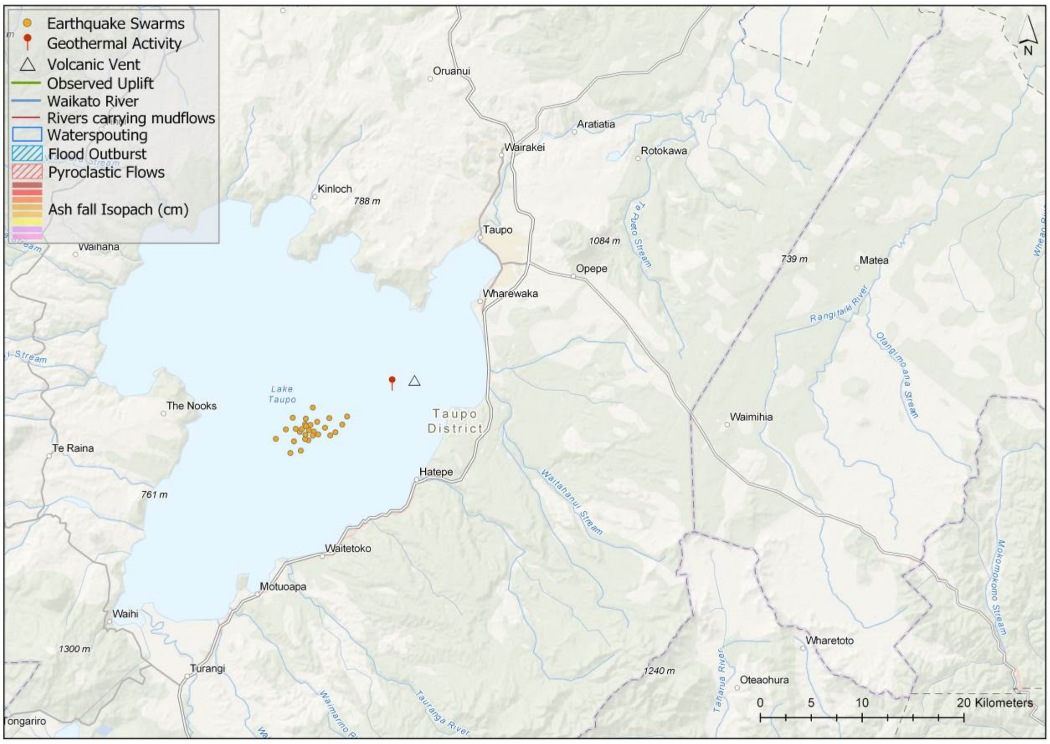

*Figure 4.2.8: **Map U4:** Depicting phenomena experienced in September and October of 2023.*

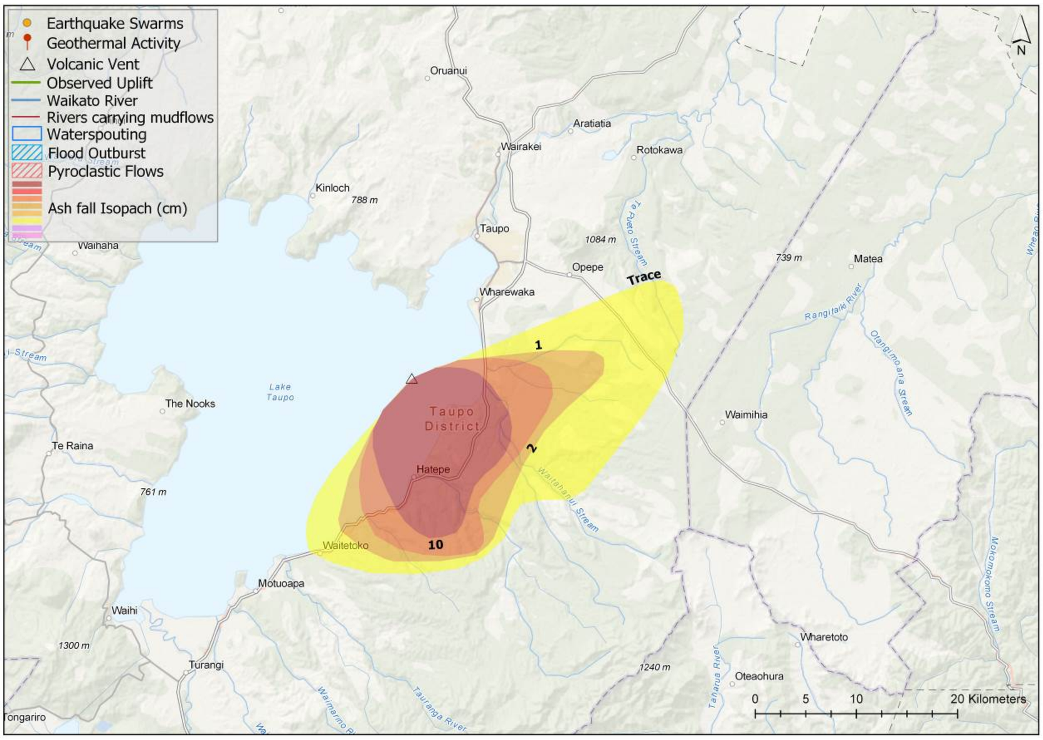

*Figure 4.2.9: **Map E1:** Eruption Phase One, depicting phenomena experienced in November of 2023.*

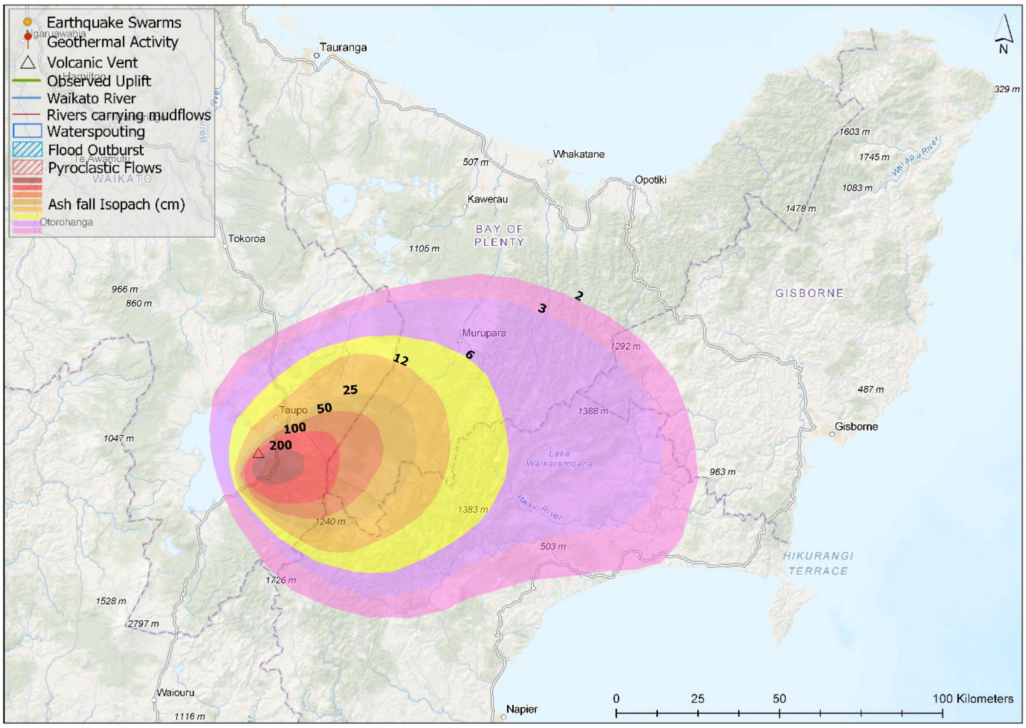

*Figure 4.2.10: **Map E2:** Eruption Phase Two, depicting phenomena experienced in November of 2023.*

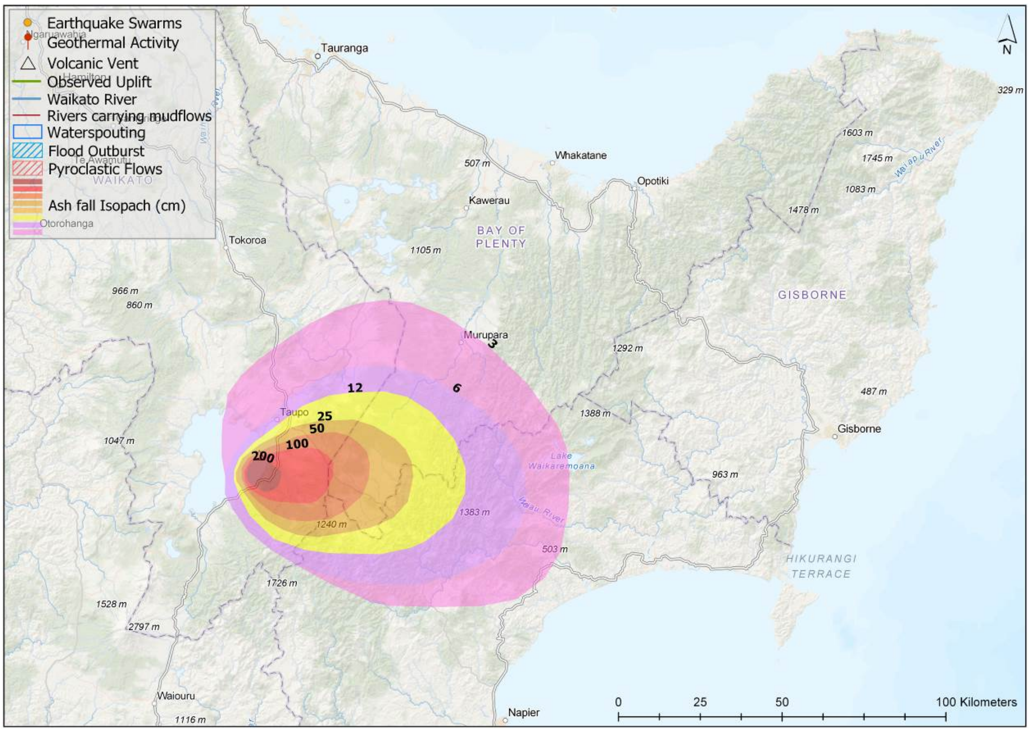

*Figure 4.2.11: **Map E3:** Eruption Phase Three, depicting phenomena experienced in November of 2023.*

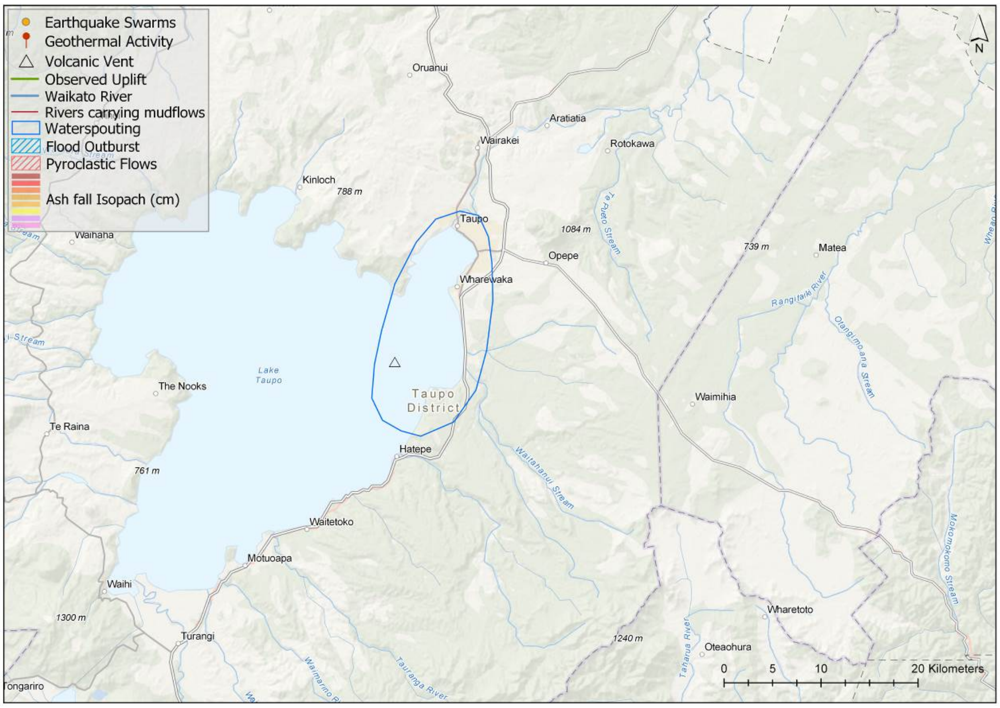

Figure 4.2.12: ***Map E4:*** *Eruption Phase Four, depicting phenomena experienced in November of 2023.*

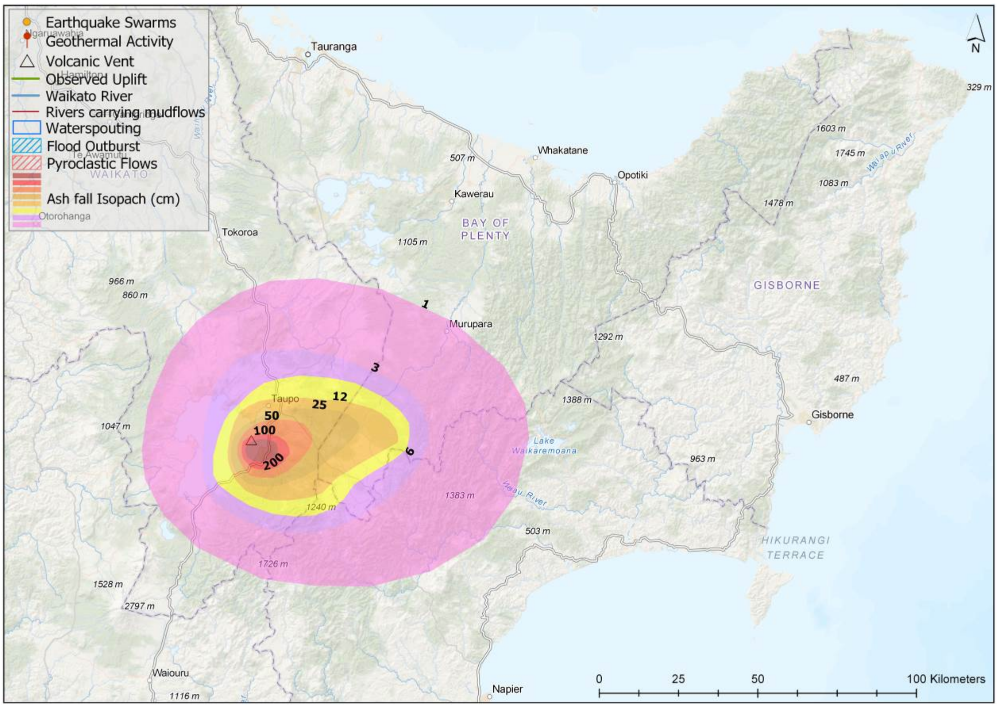

Figure 4.2.13: ***Map E5:*** *Eruption Phase Five, depicting phenomena experienced in November of 2023.*

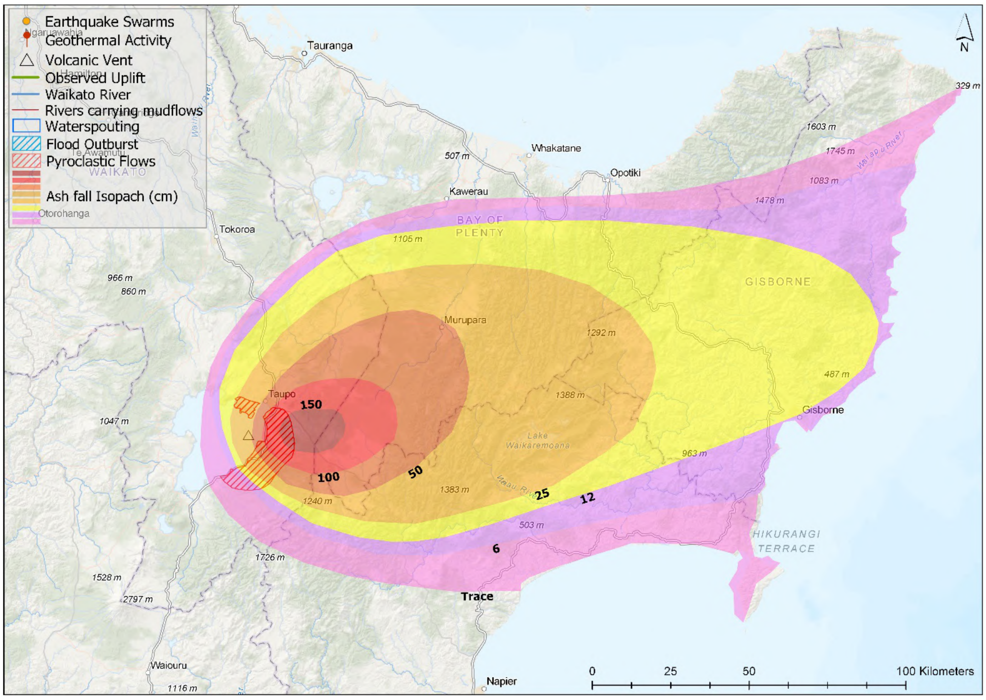

Figure 4.2.14: ***Map E6a:*** *Eruption Phase Six, depicting phenomena experienced in November of 2023.*

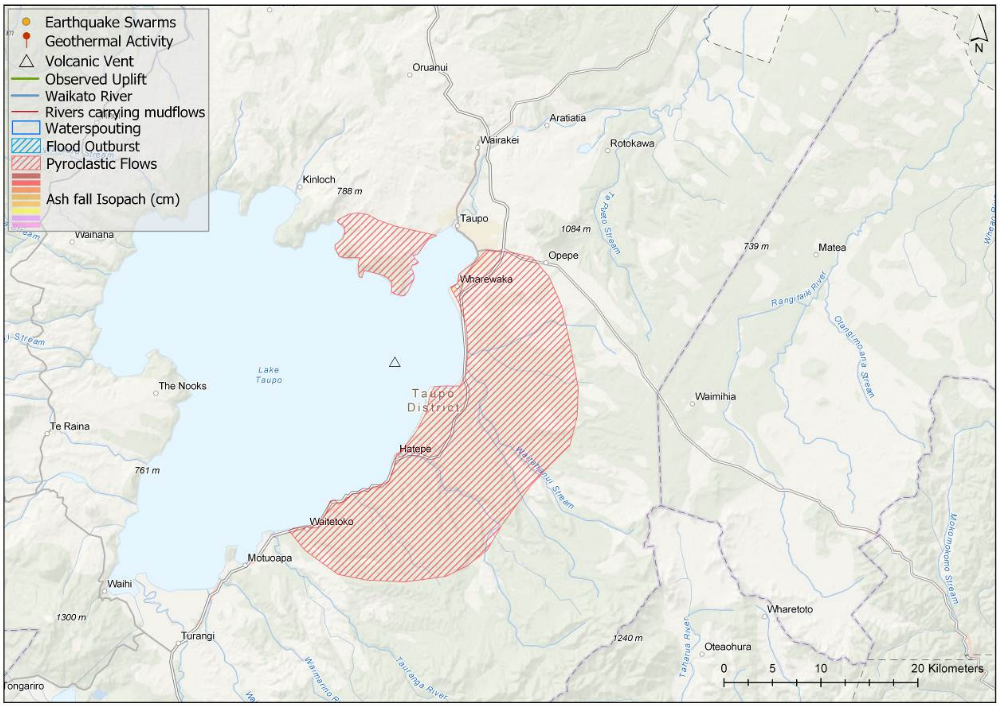

Figure 4.2.15: ***Map E6b:*** *Eruption Phase Six, depicting phenomena experienced in November of 2023. A closer view of the early ignimbrite flows in Figure 4.2.14.*

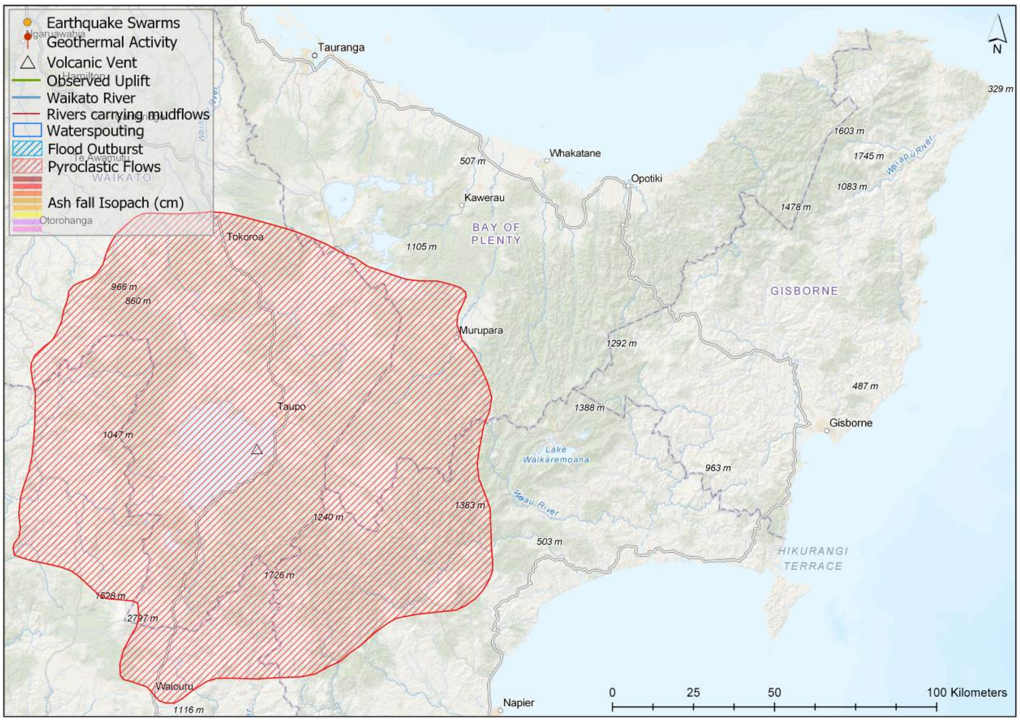

Figure 4.2.16: ***Map E6c:*** *Eruption Phase Six, depicting phenomena experienced in November of 2023.*

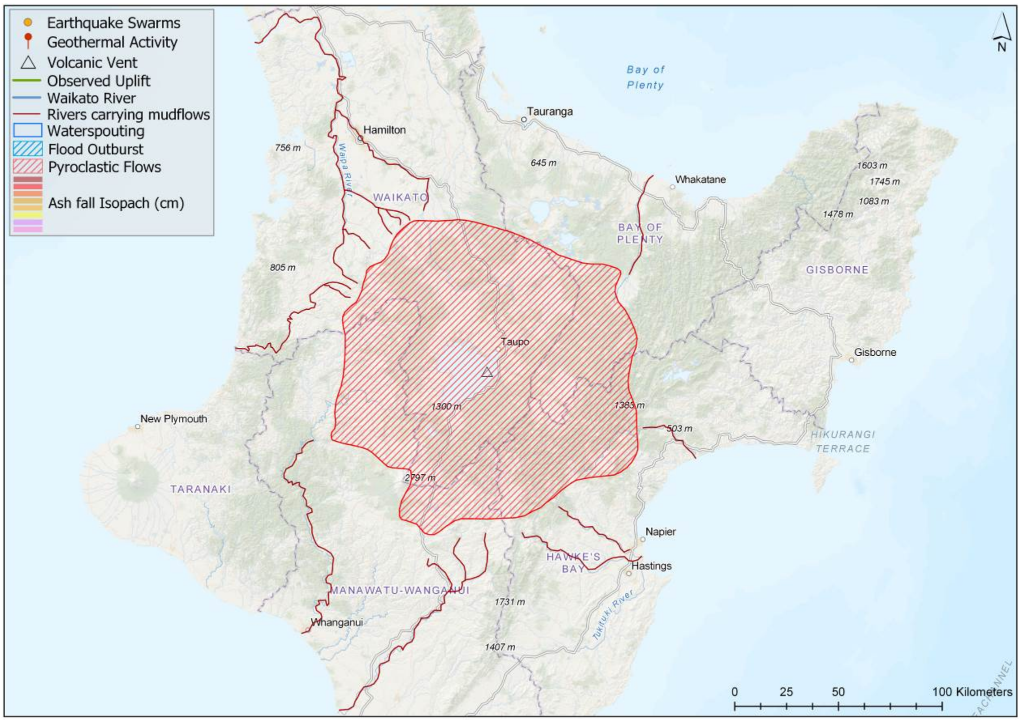

Figure 4.2.17: ***Map PE1:*** *Hours to Months Post-Eruption, depicting phenomena likely experienced post November 2023.*

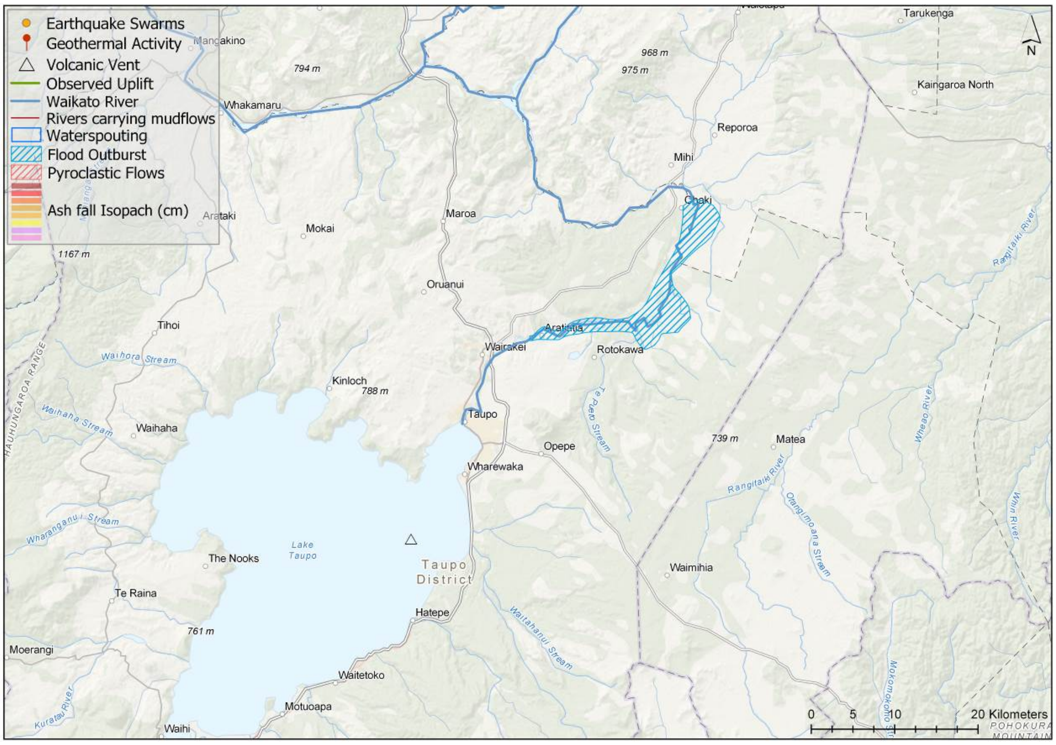

*Figure 4.2.18: **Map PE2:** Months to Decades Post-Eruption, depicting phenomena likely experienced post November 2023.*

5 SUMMARY

This research project provided the opportunity to map the breadth of stakeholders involved in silicic volcanism in A-NZ, as well as their respective requirements in order to appropriately prepare for and respond to caldera unrest and/or eruption events. The information and insight gained from these stakeholder engagements throughout the scenario development process has demonstrated the breadth of information requirements, factors, and decisions that inform what happens within volcanic risk management in A-NZ (reflected in *Chapter 3*). The findings from the engagements demonstrated that each group eventually found common attributes that they required to build an absolute bare minimum scenario around. These commonly shared requirements allowed this research to develop a consistent foundation for scenario development through the ECLIPSE Scenario Framework, and used the ECLIPSE Scenarios as exemplars of how the framework could evolve into tangible scenarios. This consistent, common foundation allows stakeholders and end-users to take this base step and further develop it to cater to more advanced applications (e.g. story-telling or science gap analysis), clearly demonstrating that the scenario development process was crucial in the individual scenario(s)' development – a clear benefit in the ECLIPSE Scenario Framework. It is also notable that without the engagement process and the co-production methods it is likely that each one of these stakeholder groups could have built their own scenarios, however, it is likely each of those scenarios would have lacked one or more attributes from another groups' discipline, therefore, missing an important part of the volcanic risk management picture – which is often where errors are made in the response to real-life events and/or disasters.

5.1 LIMITATIONS

This section outlines the limitations presented by the research methodology behind the ECLIPSE Scenario Framework and ECLIPSE Scenarios (*Section 5.1.1*) as well as specific limitations of the attributes present within the ECLIPSE Scenario Framework (*Section 5.1.2*). Recommendations to further develop and move past these limitations in outlined in *Section 5.3*.

5.1.1 Limitations of the Methodology

Due to the finite timeframe of the research project, parts of the methodology could not be completed. These steps were;

- a more robust evaluation phase and,
- a more robust inclusion of the social and cultural environments in both the ECLIPSE Scenario Framework and ECLIPSE Scenarios.

Ideally, another stage of evaluation interviews should be undertaken, particularly as the set undertaken in this project only captured responses from CDEM, Industry, NEMA, and GeoNet groups – which is only four of seven of the key stakeholder groups outlined at the beginning of this project. This second evaluation would allow the researcher to refine the current framework version (2.2) and then re-present it to the same stakeholders (and those who were missing in the first set of interviews) and evaluate those additions or changes from the ESFE Interviews. This would benefit the framework as it would continue to develop in the desired direction of the key stakeholders and end-users.

The social and cultural environments of volcanic risk management are often excluded from research in favour of more in-depth development on the physical science and built environment attributes. The research presented here attempted to accommodate the social and cultural environments but, as it was not the initial objective of the research project, the attributes present from these environments in the ECLIPSE Scenario Framework and ECLIPSE Scenarios are a basic attempt. However, by undertaking this research process, it has highlighted this gap and allows for the volcanic risk management community, and the ECLIPSE community specifically, the opportunity to ask the right questions moving forward, continuing to more robustly develop these gaps in the framework and scenarios.

5.1.2 Limitations of the ECLIPSE Scenario Framework

As stated throughout *Sections 3.2-3.3*, the attributes and factors included in the ECLIPSE Scenario Framework are not the "be all, end all" of potential attributes and factors that could or should be included. The level of detail provided for each section or sub-section is also not restrained to this version of the framework. These attributes and factors, and their level of detail, can be expanded further within the ECLIPSE programme and/or externally with individual stakeholders.

Furthermore, it is important to acknowledge that while the ECLIPSE Scenario Framework attempts to open dialogue surrounding the uncertainty of individual hazards, impacts and overall risk, event outcome uncertainty is not necessarily improved as a result. This is as the outcomes are intrinsically related to the chaotic behaviour of volcanic systems, where small changes below the surface can result in substantial changes in behaviour at the surface and can often be difficult to identify or forecast (Barclay et al., 2008).

5.2 Conclusions

The aim of this thesis was to develop a modular, adaptable framework for the development of scenarios to underpin the management of A-NZ's caldera volcanic hazard risk within the ECLIPSE programme (as stated in *Section 1.2*). This involved using co-production methods to combine scientific, practitioner, and local knowledge from all perspectives and applications of volcanic risk management (Objective One). To inform the framework's development, information was required from seven diverse groups (Regional CDEM Groups, GeoNet, Industry, Lifeline Utilities Groups, Iwi, NEMA, Research Scientists), and collected from engagement workshops and discussions throughout the research project (*Chapters 2 and 3*; Objective Two). These engagements involved presenting stakeholders with the ECLIPSE Scenario Framework and/or one of the ECLIPSE Scenarios (*Chapters 3 & 4*). The ECLIPSE Scenario Framework and ECLIPSE Scenarios were then presented in one-on-one interviews and evaluated for their potential usefulness and usability by stakeholders (*Chapter 3;* Objective Three). The main conclusions of these engagements are outlined below.

5.2.1 The ECLIPSE Scenario Framework (*Chapter 3*)

The ECLIPSE Scenario Framework proved to be a useful and useable resource for stakeholders, with all groups stating that the framework was a good foundation for combining cross boundary wants and needs from various stakeholder groups. This ECLIPSE Scenario Framework has given the disaster risk management community, and specifically the ECLIPSE community, a tangible output to host discussions around volcanic risk management from and highlighted gaps in the current co-production development methods (such as limited opportunities within individual projects to properly characterise all disaster risk management environments, *Figure 1.2*).

5.2.2 The ECLIPSE Scenarios (*Chapter 4*)

The two pillar scenarios, ECLIPSE Scenario A: The Taupō Unrest Scenario and ECLIPSE Scenario B: The Taupō Eruption Scenario, proved to be helpful in communicating the ECLIPSE Scenario Framework to stakeholders and allowing them to understand how the framework worked. All stakeholders interviewed stated that they would use or implement the scenarios in some way, relevant to their discipline, and that they were keen to continue developing and adapting the scenarios within their own organisations, and collaboratively with other external stakeholders.

5.2.3 Summary of Conclusions

Given the geographical location of A-NZ's caldera volcanoes and their potential for prolonged, disruptive unrest and/or high-impact eruptions, caldera risk management is of significant importance to A-NZ and the stakeholders that play a role in volcanic risk management. Having a framework that pulls together important aspects of the hazards and impacts associated with caldera volcano events, undertaken through robust co-production methods, supports volcanic risk management, as noted throughout workshops and interviews with stakeholders.

Overall, this research has demonstrated that using co-production methods with diverse, key stakeholders and participation by those stakeholders in the research development process can provide improvement in understanding each other's wants and needs for translating, communicating, and applying volcanic risk management towards A-NZ's caldera volcanoes.

We hope that the outputs of the engagements and this thesis continue to help inform and support co-production actions to manage and communicate caldera volcano risk in A-NZ.

5.3 RECOMMENDATIONS

5.3.1 Further Evaluate the ECLIPSE Scenario Framework

Due to the time constraints of a 12-month MSc thesis, only one set of evaluation interviews could be held, with only a limited number of representatives from each key stakeholder group (see *Table 2.1*). For future co-production development of the ECLIPSE Scenario Framework and ECLIPSE Scenarios, it is recommended another set of interviews is held with both the same set of stakeholders and those who could not be involved in the set undertaken in this thesis (namely Iwi, Research Scientists, and Lifelines).

5.3.2 Further Development of the ECLIPSE Scenarios

Due to the time constraints of a 12-month MSc thesis, only two pillar scenarios were developed (*Chapter 4*). These two scenarios encapsulate the two main types of events from one of A-NZ's calderas that were heavily requested throughout the engagement process; a scenario addressing unrest from a caldera and a scenario demonstrating a large eruption by geologic constraints. Although both these scenarios are credible representations of possible volcanic behaviour from TaVC, these do not represent the full breadth of events that could occur from Taupō, neither do they represent the full breadth of events that could occur from other caldera centres in the TVZ (such as events from Okataina or Rotorua calderas). Because of this, it is recommended that more scenarios are developed, with stakeholders, using the ECLIPSE Scenario Framework.

These ECLIPSE Scenarios developed also had more robust attributes from the built and natural environments and tend to cater to the more physical science-focused applications within the ECLIPSE Scenario Framework. It is therefore recommended that more specific future research is undertaken to improve the understanding of the social, cultural, and economic environments in the context of caldera risk and implemented into these scenarios (and the framework).

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APPENDICES

Appendix A TERMINOLOGY

A.1 DISASTER RISK MANAGEMENT TERMINOLOGY

Acceptable Risk: Risk that an individual is willing to accept, or that a public official is prepared to allow an individual or community in their charge to accept, in return for perceived benefits of taking that risk (Newhall & Hoblitt, 2002).

Disaster: A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts (UNDRR, 2017).

Disaster Risk: the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, and vulnerability (UNDRR, 2017).

Disaster Risk Assessment: A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend (UNDRR, 2017).

Disaster Risk Management: The application of disaster risk reduction polices and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to strengthening of resilience and reduction of disaster losses (UNDRR, 2017).

Disaster Risk Reduction: Aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development (UNDRR, 2017).

Event-tree: A graphical, tree-like representation of event in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes. For graphical and conceptual simplicity, events at any given level of the tree need not be mutually exclusive or exhaustive (Newhall & Hoblitt, 2002).

Exposure: The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas (UNDRR, 2017).

Hazard: A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. These may be natural, anthropogenic, or socio-natural in origin. (UNDRR, 2017).

Intermediate-term: Pertaining to the coming months and, occasionally, years. Intermediate-term hazard is typically estimated when a volcano is restless (or even erupting), but the unrest (or eruption) is not changing rapidly (Newhall & Hoblitt, 2002).

Lifeline Utilities: The physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society (UNDRR, 2017). *Also known as "critical infrastructure".*

Long-term: Pertaining to the coming years, decades, centuries and longer. For most long-term hazard estimates, the volcano in question is dormant and any seismicity, geodetic change or fumarolic activity is at background levels (Newhall & Hoblitt, 2002).

Mitigation: The lessening of minimising or the adverse impacts of a hazardous event (UNDRR, 2017).

Multi-hazard: Specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNDRR, 2017).

Preparedness: The knowledge and capacities developed by governments, response and recovery organisations, communities and individuals to effectively anticipate, respond to and recovery from the impacts of likely, imminent or current disasters (UNDRR, 2017). *Can be used in place of "readiness".*

The 4 R's: The New Zealand integrated approach to civil defence emergency management can be described by the four areas of activity, known as the '4 Rs'; reduction, readiness, response and recovery (NEMA, 2013).

Reduction: Identifying and analysing long-term risks to human life and property from hazards; taking steps to eliminate these risks if practicable, and, if not, reducing the magnitude of their impact and the likelihood of their occurring (NEMA, 2013).

Readiness: In order to be ready for, and to reduce the effects of an emergency, agencies need to incorporate risk management into their normal activities. They also need to plan, train, and exercise for emergencies, and incorporate lessons identified into their planning and processes (DPMC, 2015). *Can be used in place of "preparedness".*

Response: Involves actions taken immediately before, during or directly after an emergency to save lives and property, and to help communities recover. Agencies respond to emergencies by activating their own plans and coordinating their activities with other agencies to manage the consequences of the emergency (DPMC, 2015).

Recovery: The coordinated efforts and processes to bring about the immediate, medium and long-term holistic regeneration and enhancement of a community following an emergency (NEMA, 2013).

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (UNDRR, 2017).

Sendai Framework: Prevent new and reduce existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience (UNDRR, 2015).

Short-term: Pertaining to the coming minutes to weeks. Short-term hazards are typically estimated when unrest (or an eruption) is changing rapidly (Newhall & Hoblitt, 2002).

Vulnerability: The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR, 2017). It can be stated in terms of a probability of damage, or as a percentages of the total exposed assets expected to be affected by a given peril (Jolly & de la Cruz, 2015).

A.2 VOLCANIC TERMINOLOGY

Ash fall: Fine material ejected from a volcano during an eruption. Derived of volcanic glass, rock and crystal particles and is carried in the eruption column (GNS Science, 2010c).

Andesite: Grey to black volcanic rock with between about 52 and 63 weight percent silica. Andesite magma commonly erupts from stratovolcanoes as thick lava flows and can also generate strong explosive eruptions to form pyroclastic flows and surges and enormous eruption columns (USGS, 2016).

Basalt: Volcanic rock that is characteristically dark in colour and contains 45 to 53 percent silica. Basaltic magma is commonly produced from shield volcanoes (USGS, 2016).

Caldera: A depression in the ground formed by the withdrawal of underground magma causing the roof of the magma chamber to collapse (Potter, Scott & Jolly, 2012).

Debris Avalanche: Moving masses of rock and soil that occur when the flank of a mountain or volcano collapse and slides downslope, incorporating everything in its way. They can transform into water-rich lahars as they travel (USGS, 2016).

Dormant: Generally, means not-in-eruption (Potter, Scott & Jolly, 2012).

Earthquake Swarms: Many earthquakes occurring close together in time and space, usually of a similar size (Potter, Scott & Jolly, 2012). *Can also be known as "Seismic Swarms".*

Episode of Unrest: A period of unrest of unspecified duration, preceded and followed by relative quiescence of equal or longer duration. Typically, unrest lasts several weeks to years and quiescence lasts several years to centuries (Newhall & Dzurisin, 1988).

Eruption Column/Plume: The ascending, vertical part of the mass of erupting debris and volcanic gas that rises directly above a volcanic vent. Higher in the atmosphere, columns usually spread laterally into plumes or umbrella clouds (USGS, 2016).

Fissures: Large cracks in the ground or line of vents (Potter, Scott & Jolly, 2012; GNS Science, 2012).

Fumarole: Vents, that occur along tiny cracks, long fissures, clusters and/or on the surfaces of lava flows or thick deposits of pyroclastic flows, from which volcanic gases escape into the atmosphere (USGS, 2016).

Gas Poisoning: Volcanic gases include carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrochloric acid (CHl), hydrofluoric acid (HF), hydrogen sulphide (H2S) and radon (Rn). Can cause health effects such as discomfort and/or asphyxiation (Potter, Scott & Jolly, 2012).

Ground deformation: (Ground movement including uplift or subsidence) occurs as a result of magma moving beneath the ground surface, before, during and after eruptions. Can range from millimetres to metres, can affect wide areas and may cause fissures (Potter, Scott & Jolly, 2012).

Hydrothermal Explosions: Small gas and/or steam eruptions that can also occur without the influence of magma due to normal hydrothermal system processes or during drilling (Potter, Scott & Jolly, 2012).

Isopach: A line on a map that connects geologic units of equal ash or thickness deposits from an explosive eruption (USGS, 2016).

Ignimbrite: The rock formed by widespread deposition and consolidation of pyroclastic flows (USGS, 2016).

Lahars: Are "mudflows" which are mixtures of volcanic ash, blocks and water, formed on volcanoes. The source can be from a crater lake, a dam collapse or heavy rainfall washing ash from the slope of a volcano (GNS Science, 2010c).

Lava: Magma (molten rock) erupted at the ground surface (GNS Science, 2012).

Lava Dome: Mound that forms when viscous (sticky) lava is erupted slowly and piles up over the vent rather than moving away as a lava flow (GNS Science, 2012).

Lava Fountain: Fountain of runny lava from a vent or fissure (GNS Science, 2012).

Magma: Underground molten rock (Potter, Scott & Jolly, 2012).

Magma Chamber/Reservoir: The location beneath the vent of a volcano where magma is stored prior to eruption (USGS, 2016).

Pyroclastic Flows: Hot (several hundreds of degrees Celsius), gaseous clouds formed from eruption column collapse during an eruption. These can travel hundreds of metres per second and cause total destruction of the areas they cover (GNS Science, 2010c).

Phreatic Eruption: An eruption driven by the heat from magma interacting with water (groundwater, hydrothermal systems, surface runoff, lake, sea water) (GNS Science, 2012).

Plinian: Type of eruption with a high rate of magma discharge, sustained for minutes to hours, forming tall eruption columns (20-35km) and cause wide dispersion of ash (GNS Science, 2012).

Pumice: Magma that has been "frothed up" by escaping gases and then cooled and solidified during the eruption, typically silicic in composition (USGS, 2016).

Phreatomagmatic: An eruption that involves both magma and water, which typically interact explosively, leading to an ejection of steam and pyroclastic fragments (USGS, 2016).

Phreatoplinian: An eruption where silicic magma interacts violently with abundant water, often residing in caldera lakes (Sigurdsson et al., 1999).

Rhyolite: Volcanic rock that characteristically is light in colour, contains 69 or more percent of silica. Rhyolitic lavas are viscous and tend to form thick blocky lava flows or lava domes. Rhyolite magmas tend to erupt explosively (USGS, 2016).

Supereruption: Term used to describe explosive VEI 8 eruptions from supervolcanoes that typically form a caldera (USGS, n.d.).

Supervolcano: A volcanic centre that has had an eruption of VEI 8 but often experience much smaller eruptions in between these VEI 8 supereruptions (USGS, 2015).

Surge: Ground-hugging clouds of ash, rock and volcanic gas that move at hundreds of metres per second and have temperature of several hundred degrees Celsius (USGS, 2016).

Silica: Silicon dioxide ($SiO2$), the most abundant rock-forming compound on Earth and the predominant molecular constituent of volcanic rocks and magmas (USGS, 2016).

Silicic: Describes magma that contains more than about 63 percent silica and is generally viscous, gas-rich and tens to erupt explosively (USGS, 2016).

Seismicity: The phenomenon of earthquakes caused by the brittle fracturing of rocks in Earth's crust (USGS, 2016).

Subduction: The process of the oceanic lithosphere colliding with and descending beneath the continental lithosphere (USGS, 2016).

Seiche (Seiching): A seiche is a standing wave oscillating in a body of water (NOAA, 2013).

Tephra: Any type and size of rock fragment that is forcibly ejected from the volcano and travels an airborne path during an eruption (including ash) (USGS, 2016).

Unrest: Anomalous volcanic activity that changes above normal background levels, potentially, but not necessarily, precursory to an eruption (Newhall & Hoblitt, 2002). Volcanic unrest occurs when regional tectonic and/or volcanic processes cause magma and/or its fluids to interact with pre-existing rocks and sub-surface fluids. This can cause earthquakes, ground surface deformation, fumaroles, hydrothermal explosions, and change in regional groundwater levels and spring temperatures (Potter, Scott & Jolly, 2012).

Volcanic Alert Levels (VALs): Used for the communication of the current level of volcanic activity at multiple volcanoes (Potter et al., 2015a).

Volcanic Explosivity Index (VEI): A numeric scale that measures the relative explosivity of volcanic eruptions. Volume of products, eruption cloud height, and qualitative observations are used to determine the explosivity value. The scale is open-ended (largest volcanic eruptions in history, supereruptions, given VEI 8) and is logarithmic, with each interval on the scale representing a tenfold increase in observed ejecta criteria, with the exception of between VEI 0, VEI 1 and VEI 2 (USGS, 2017).

Volcanic Unrest Index (VUI): A semi-quantitative rating of unrest intensity at caldera volcanoes. Integrates the intensity of multiple volcanic unrest parameters attained through monitoring, observations, and modelling into one number per time period of elevated activity (Potter et al., 2015a).

Viscosity: Resistance of fluid (liquid or gas) to a change in shape, or movement of neighbouring portions relative to another. High viscosity magma is sticky, while low viscosity is runny and flows faster (Encyclopaedia Britannica, 2018).

Vent: Any opening at the Earth's surface through which magma erupts or volcanic gases are emitted (USGS, 2016).

Appendix B ECLIPSE Scenario Development Workshop

B.1 ECLIPSE Scenario Development Workshop Outline

The ESDW began with an introductory series of presentations (*Figure B.1*) from presenters listed in *Table B.1*. This section of the workshop provided background on the ECLIPSE programme (*Section 1.1.1*), the scenario development approach (*Chapter 2*), workshop objectives (*Chapter 2*), and the overall context (including indigenous worldviews on volcanism, the TVZ geology, and the hazards, exposure and risks associated).

Appendix Table B.1: Presenters of the ESDW in March 2019, with their respective organisations and topics presented.

PRESENTER NAME	ORGANISATION	TOPIC PRESENTED
Tyronne (Bubs) Smith	Ngāti Tūwahretoa	Indigenous Overview
Thomas Wilson	University of Canterbury	Introductions & Exposure/Risks
Sylvia Tapuke	Toi Ohomai	Indigenous Perspectives
Colin Wilson	Victoria University	TVZ geology
Graham Leonard	GNS Science	Hazards of the TVZ

Following the introductory presentations, participants were divided into groups based on their practicing discipline for exercises one and two. These groups were CDEM, GeoNet, Industry and Lifelines, Iwi, and Research Science (*Table B.2*) – each facilitated by a facilitator (*Table B.3*).

Appendix Table B.2: Organisations that attended the ESDW in March 2019, related to their broad stakeholder group.

STAKEHOLDER GROUP	ORGANISATIONS
CDEM	Bay of Plenty CDEM Waikato CDEM
GeoNet	GNS Science

	GeoNet Volcano Team
Industry and Lifelines	Federated Farmers Ministry for Primary Industries (MPI) Rural Support Trusts University of Canterbury
Iwi	Ngāti Tūwahretoa Toi Ohomai Te Arawa
Research Science	Massey University University of Canterbury Victoria University University of Auckland

Appendix Table B.3: Facilitators involved in the ESDW and their related groups facilitated.

FACILITATOR NAME	DISCIPLINE GROUP	"JIG-SAWED" GROUP
Graham Leonard	GeoNet	Three
Lucy Kaiser	Iwi	One
Mary Anne Thompson	CDEM	Four
Simon Barker	Research Scientists	Four
Thomas Wilson	Industry and Lifelines	Two

B.1.1 Exercise One

Exercise One, with participants in discipline-based groups (*Table B.2*), asked broad questions regarding the nature of scenarios and their uses. The goal was for participants to discuss requirements they would want or need to have implemented into the potential scenarios and framework. Three broad questions were asked around the use, factors and format of scenarios;

- In your current role, how might you use caldera eruption scenarios?
- To be useful, what do these scenarios need to have? What are the factors, issues and attributes which all make the scenarios useful and useable for our ECLIPSE community of practice?
- To be useable, how should these scenarios be available?

Participants were given 30 minutes to brainstorm, with the facilitator recording, ideas and answers to these questions, which are collated and summarised in *Chapter 3* and *Appendix Section B.3*.

B.1.2 Exercise Two

Exercise Two, with participants remaining in discipline-based groups (*Table B.2*), involved the critique of a traditional unrest-to-eruption exemplar scenario. The scenario followed the unrest behaviour through to the eruption cease of the historic 1314 AD Kaharoa eruption from the OVC. Participants were asked to critique the scenario's potential usefulness and application through the questions listed below;

- Is it useful? How might you use it?
- Anything missing? What frustrates you?
- Where possible, explain why?

Participants were given 30 minutes to undertake a critical review of the traditional scenario and brainstorm, with the facilitator recording, ideas about what was provided that did already suit their neds, what did not suit their needs, what was missing, and how the scenario could be improved. The results are collated and summarised in *Chapter 3* and *Appendix B.3*.

B.1.3 Exercise Three

After Exercises One and Two were completed, participants were asked to re-form into four "jig-sawed" groups for Exercise Three. This meant that at least one representative from each of the five key stakeholder group (*Table B.2*) was present in each of the four "jig-saw" groups. The aim of this "jig-sawing" was to enable comparison and contrast of the potential similarities and differences between each discipline in regards to the scenarios and framework development.

Exercise Three aimed to answer three questions similar to that of Exercise One (*B.1.1*) but with a focus on identifying the similarities and differences in needs and priorities across the five different disciplines. The exercise also addressed how the groups were independent of or co-dependent on each other in particular aspects. This exercise further focused on assessing what kind of scenarios would need to be developed in order to challenge the groups in their disaster risk management mitigations, strategies and plans. The questions posed to participants were;

- What are the most important potential uses or applications of the scenarios?
- What are the tricky or challenging situations you think are more important to include?
- To be useful, what do these scenarios need to have? What do you need to know?

If participants wanted to, or if facilitators felt that it was necessary in order to prompt discussion and ideas, optional qualitative scenarios (*Tables B.7-B.8*) were provided. Each group was offered one hazard scenario and one impact scenario. These scenarios did not match each other in that the impact scenario was not derived from the hazard scenario (as further indicated by the labels given). These broad and brief scenarios allowed a more simplistic look at possible scenario templates and pathways that future scenarios could be developed to accommodate.

Participants were given 30 minutes to brainstorm, with the facilitator recording, ideas and answers to these questions (and, if used, qualitative scenarios), which are collated and summarised in *Chapter 3* and *Appendix B.3*.

B.2 ECLIPSE Scenario Development Workshop Resources

The 1314 AD Kaharoa Eruption event was the historic event used as a traditional scenario example for the ESDW. The scenario unrest and eruption timeline and hazard footprints (*Figures B.2, B.4-B.6 and Table B.1*) were derived from Johnston et al. (2000),

ECLIPSE Scenario Development Workshop

GNS Science Wairakei
25 March 2019

I. **INTRODUCTION TO THE DAY** (15 minutes)
- Mihi.
- Housekeeping.
- Introductions.

Go around the room – give name and role/organization.
- Overview of ECLIPSE project.

Purpose and scope.
- Scenarios Overview.

What are they? How might they be used? Goal of scenarios within ECLIPSE.
- Overview of Workshop

Objectives, what we hope to achieve, and how the information will be used.

II. **ICEBREAKER** (10 minutes)
- Introductions to one another.

Chat to someone you don't know well/at all (5 minutes)
- Quick activity (5 minutes)

What would you do tomorrow if…?

III. **SETTING THE CONTEXT** (30 minutes)
- Overview of the indigenous worldviews of volcanism.
- Overview of caldera volcanism in the Taupō Volcanic Zone.
- Overview of the hazards, risks, and exposures.

The 10 volcanic hazards, what is exposed?, what is vulnerable?, lessons from other large silicic eruptions.
- How does New Zealand manage volcanic risk?

IV. **EXERCISE 1** (30 minutes)
- Reflect on the concept of scenarios and how they might be useful in your community of practice.

In discipline-based groups discuss how caldera eruption scenarios might be used within your roles and what key elements are needed to make a useful scenario?
- Report back after 20 minutes

V. **EXERCISE 2: Kaharoa Scenario Critique** (30 minutes)
- Critical critique of a traditional eruption scenario based on the ~1305AD Kaharoa eruption.
- Consider the applications, strengths, and weaknesses of an example scenario.

Is it useful? How might use it? Anything missing? What frustrates you?
- Report back after 20 minutes

VI. **AFTERNOON TEA** (20 minutes)

VII. **EXERCISE 3: Bigger Picture Thinking** (30 minutes)

In jig-sawed groups, drawing on previous exercises, discuss what are the potential uses for these scenarios?, what are the tricky or challenging situations that are important to include?, what do the scenarios need to be useful?
- Brainstorm around scenario variables that are useful for exploring the complexities of risk management.
- A focus on tricky or challenging situations for those involved.

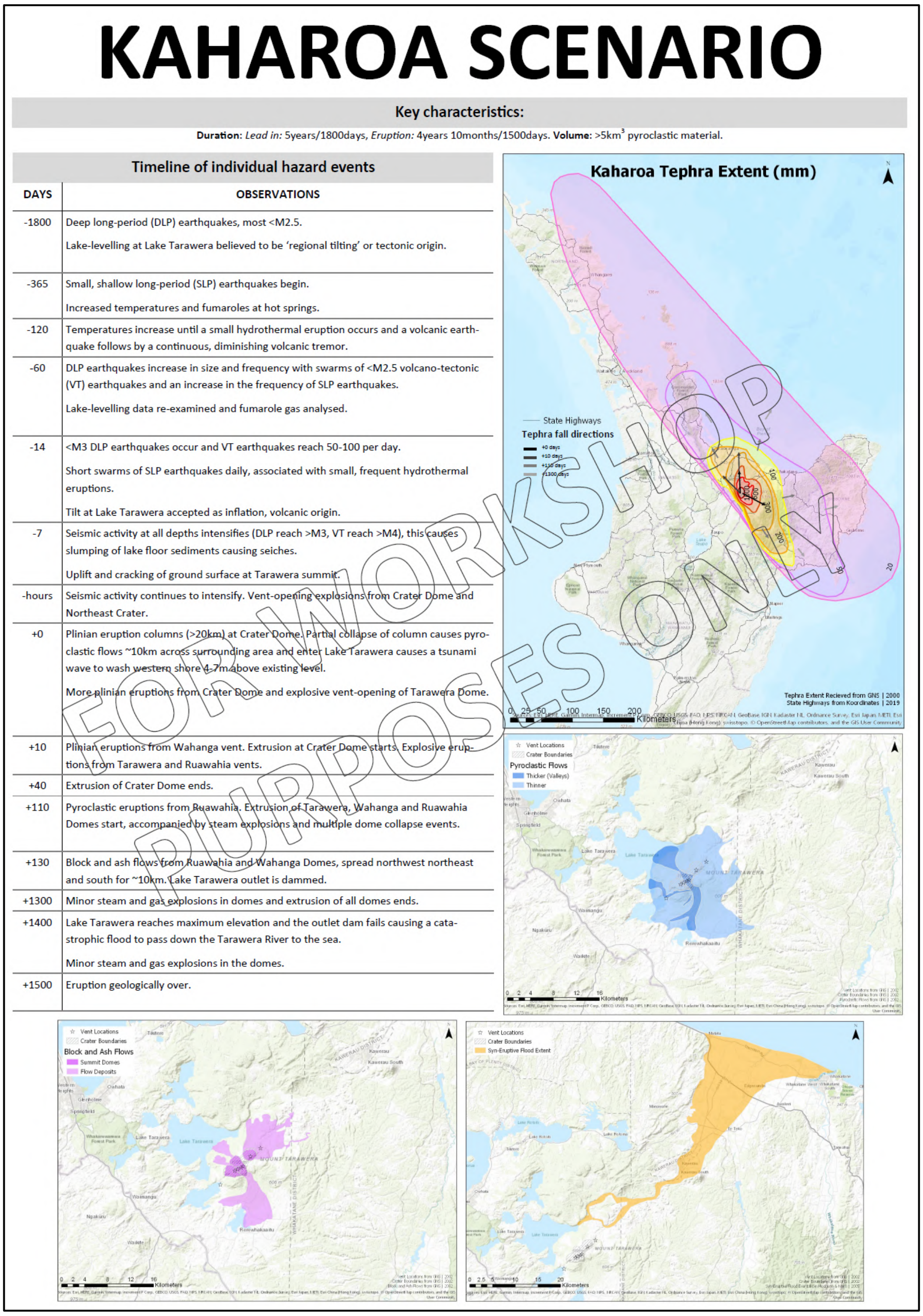
Qualitative scenarios, one hazard focused and one impact focused, can be provided to help thinking.
- Report back after 20 minutes

VIII. **DISCUSSION** (20 minutes)

IX. **WRAP-UP** (10 minutes)
- Where to from here?
- When will you hear from us next?
- Recap of the day.

Appendix Figure B.1: ESDW Agenda for 25th March 2019.

Nairn et al. (2001), Johnston, Nairn & Martin (2002), and Sherburn & Nairn et al. (2004) and the poster style (*Figure B.2*) was inspired by Hayes et al. (2018). The ash fall isopachs, used in *Figures B.3 and B.8-B.10*, were from Johnston et al. (2000), the building impacts data (*Figure B.7* and *Table B.2*) was from GNS Science & RiskScape (2019), and the agricultural impacts data (*Figure B.7* and *Table B.3*) was from Asure Quality (2018).

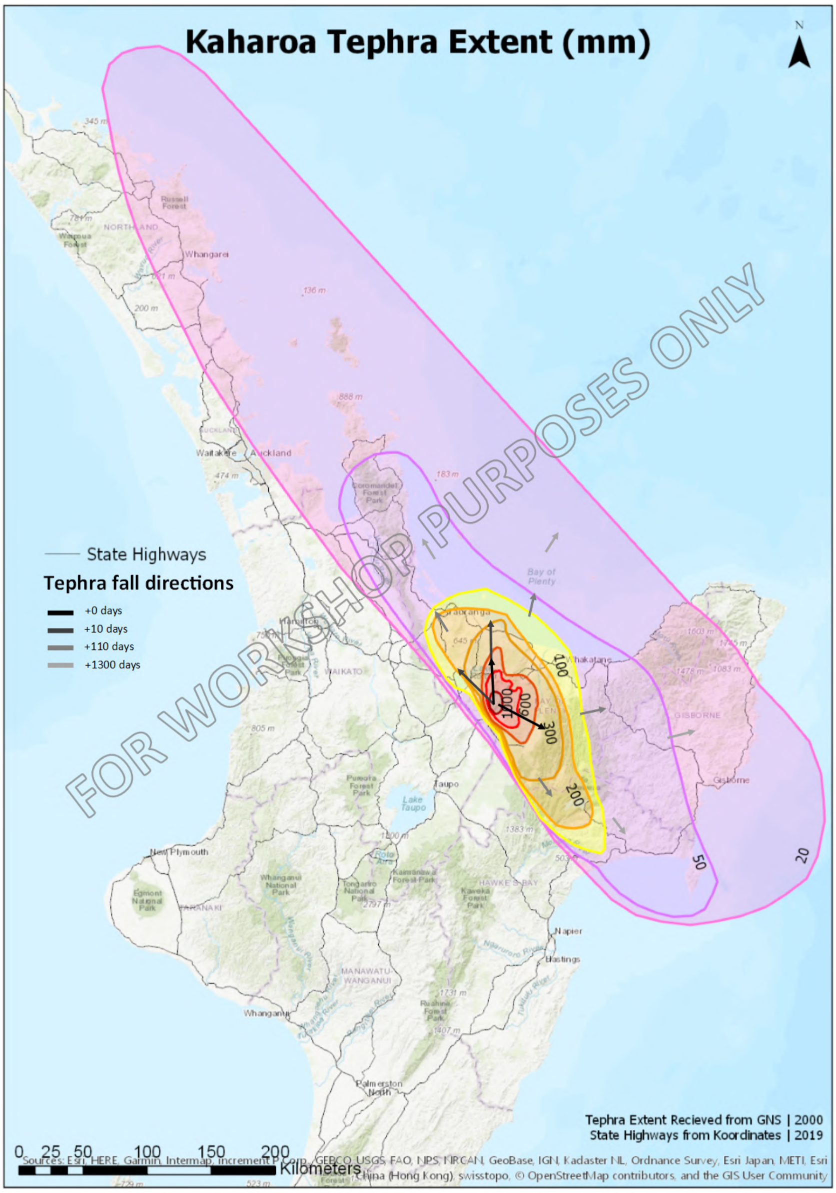


Appendix Figure B.2: 1314 AD Kaharoa Eruption poster used as an example for the ESDW in March 2019.

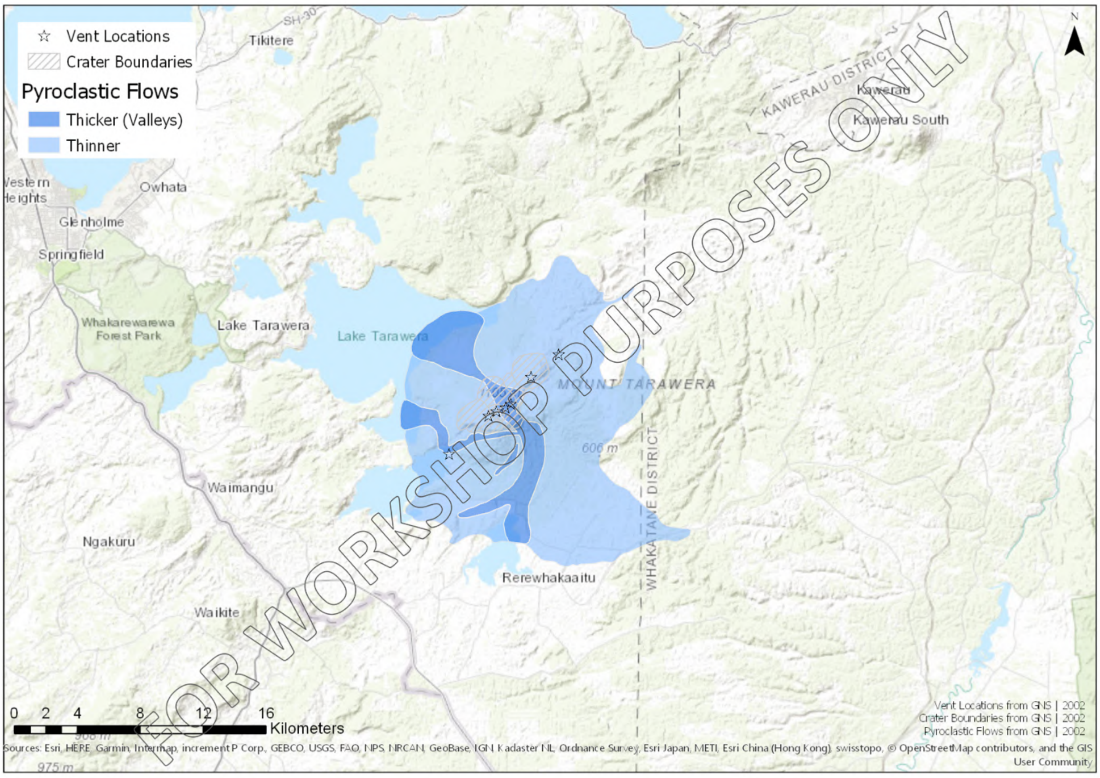
Appendix Table B.4: Timeline of individual hazard events from the 1314 AD Kaharoa Eruption poster in Figure A#.2.2 above, showing unrest and eruption.

Timeline of individual hazard events	
DAYS	**OBESERVATIONS**
-1,800	Deep long-period (DLP) earthquakes, most <M_w2.5. Lake-levelling at Lake Tarawera believed to be 'regional tilting' or tectonic origin.
-365	Small, shallow long-period (SLP) earthquakes begin. Increased temperatures and fumaroles at hot springs.
-120	Temperatures increase until a small hydrothermal eruption occurs and a volcanic earthquake follows by a continuous, diminishing volcanic tremor.
-60	DLP earthquakes increase in size and frequency with swarms of <M_w2.5 volcano-tectonic (VT) earthquakes and an increase in the frequency of SLP earthquakes. Lake-levelling data re-examined and fumarole gas analysed.
-14	<M_w3.0 DLP earthquakes occur and VT earthquakes reach 50-100 per day. Short swarms of SLP earthquake daily, associated with small, frequent hydrothermal eruptions. Tilt at Lake Tarawera accepted as inflation, volcanic origin.
-7	Seismic activity at all depths intensifies (DLP reach >M_w3.0, VT reach >M_w4.0), this causes slumping of lake floor sediments causing seiches. Uplift and cracking of ground surface at Tarawera summit.
-hours	Seismic activity continues to intensify. Vent-opening explosions from Crater Dome and Northeast Crater.
+0	Plinian eruption columns (>20km) at Crater Dome. Partial column collapse causes pyroclastic flows ~10km across surrounding area and enter Lake Tarawera and causes a tsunami wave to wash western shore 4-7m above existing level. More Plinian eruptions from Crater Dome and explosive vent-opening of Tarawera Dome.
+10	Plinian eruptions from Wahanga vent. Extrusion at Crater Dome starts. Explosive eruptions from Tarawera and Ruawahia vents.
+40	Extrusion of Crater Dome.
+110	Pyroclastic eruptions from Ruawahia. Extrusion of Tarawera, Wahanga, and Ruawahia Domes start, accompanied by steam explosions and multiple dome collapse events.

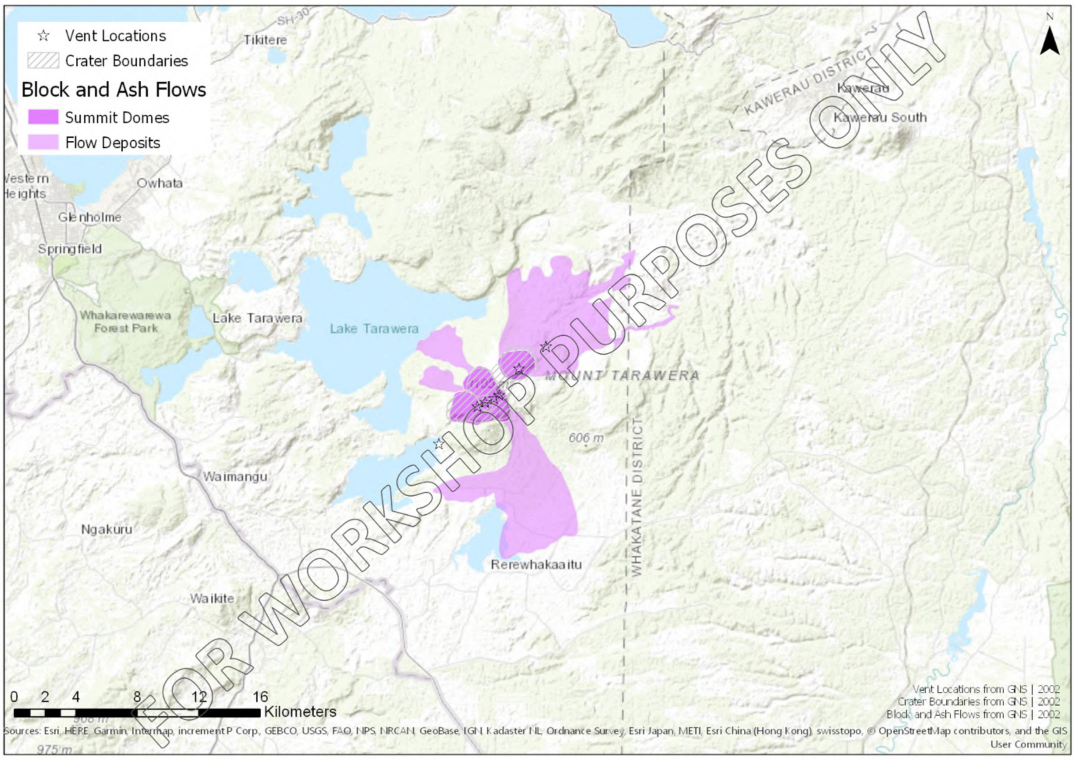
+130	Block-and-ash flows from Ruawahia and Wahanga Domes, spread northwest, northeast, and south for ~10km. Lake Tarawera outlet is dammed.
+1,300	Minor steam and gas explosions in domes and extrusion of all domes ends.
+1,400	Lake Tarawera reaches maximum elevation and the outlet dam fails causing a catastrophic flood to pass down the Tarawera River to the sea. Minor steam and gas explosions in the domes.
+1,500	Eruption geologically over.



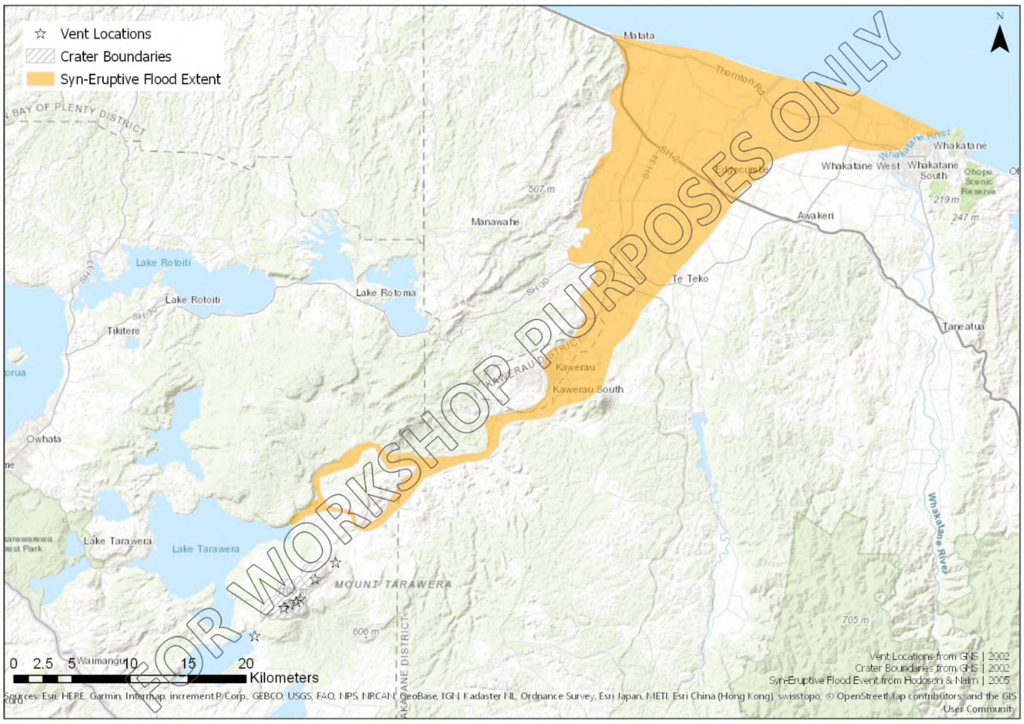
Appendix Figure B.3: 1314 AD Kaharoa Eruption isopach with wind direction changes.



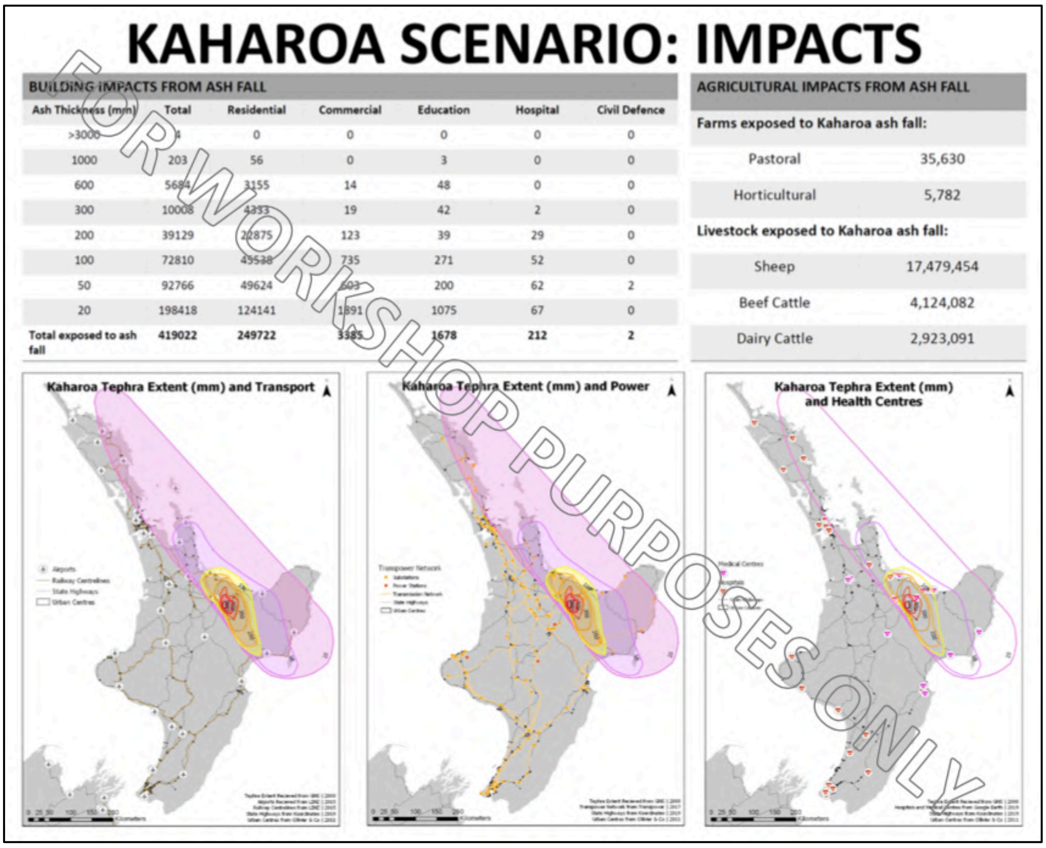
Appendix Figure B.4: Pyroclastic flows from the early eruption phase of the 1314 AD Kaharoa Eruption scenario.



Appendix Figure B.5: Block-and-ash flows from the later phases of the 1314 AD Kaharoa Eruption scenario.



Appendix Figure B.6: Flood event experienced in the final stages of the 1314 AD Kaharoa Eruption scenario.



Ash Thickness (mm)	Total	Residential	Commercial	Education	Hospital	Civil Defence
>3000	4	0	0	0	0	0
1000	203	56	0	3	0	0
600	5684	3155	14	48	0	0
300	10008	4333	19	42	2	0
200	39129	22875	123	39	29	0
100	72810	45538	735	271	52	0
50	92766	49624	603	200	62	2
20	198418	124141	1891	1075	67	0
Total exposed to ash fall	**419022**	**249722**	**3385**	**1678**	**212**	**2**

Farms exposed to Kaharoa ash fall:	
Pastoral	35,630
Horticultural	5,782
Livestock exposed to Kaharoa ash fall:	
Sheep	17,479,454
Beef Cattle	4,124,082
Dairy Cattle	2,923,091

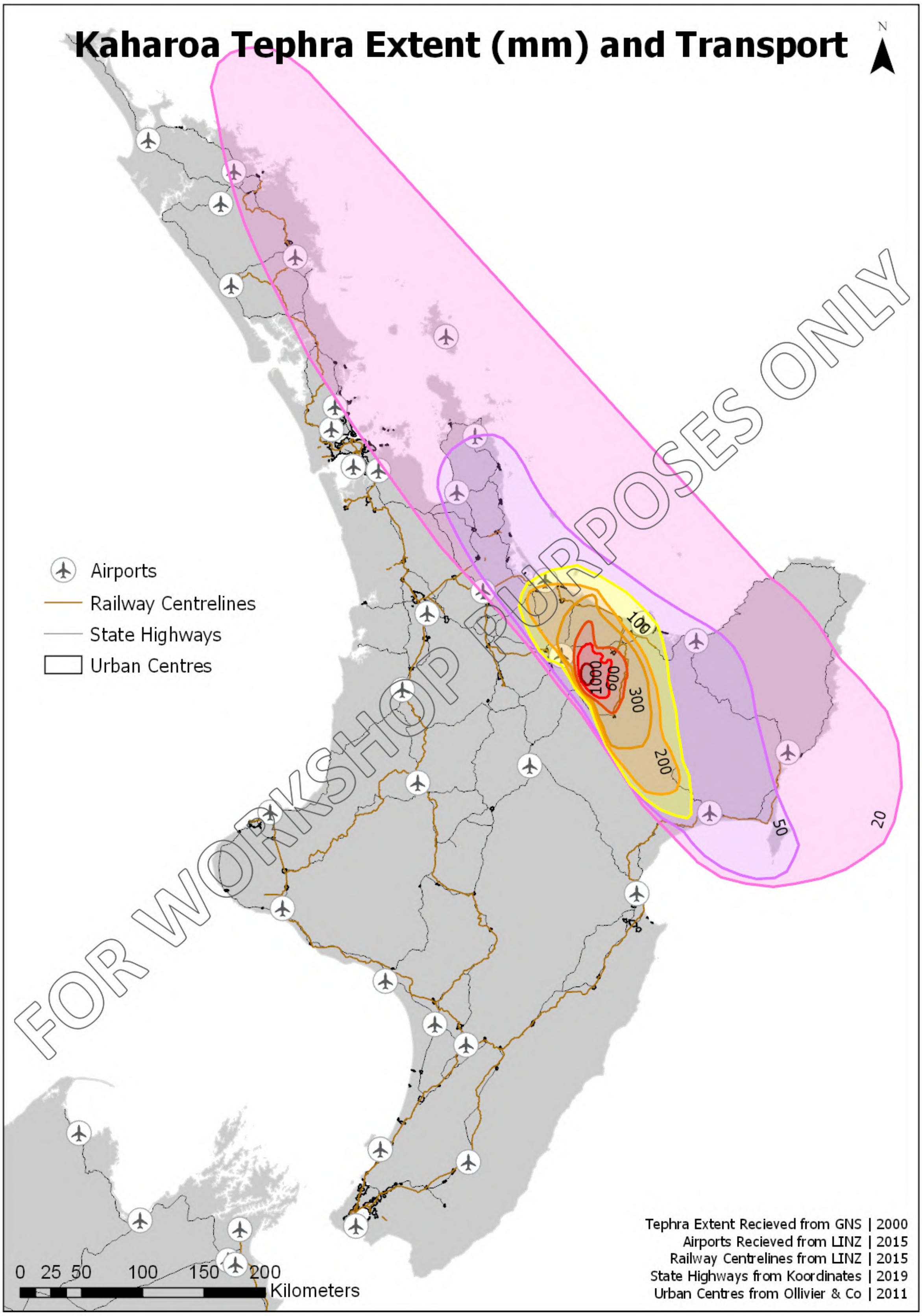
Appendix Figure B.7: 1314 AD Kaharoa Eruption scenario impacts poster used as an example in the ESDW in March 2019.

Appendix Table B.5: 1314 AD Kaharoa Eruption scenario ash fall impact on buildings from the ESDW impacts poster in Figure B.7.

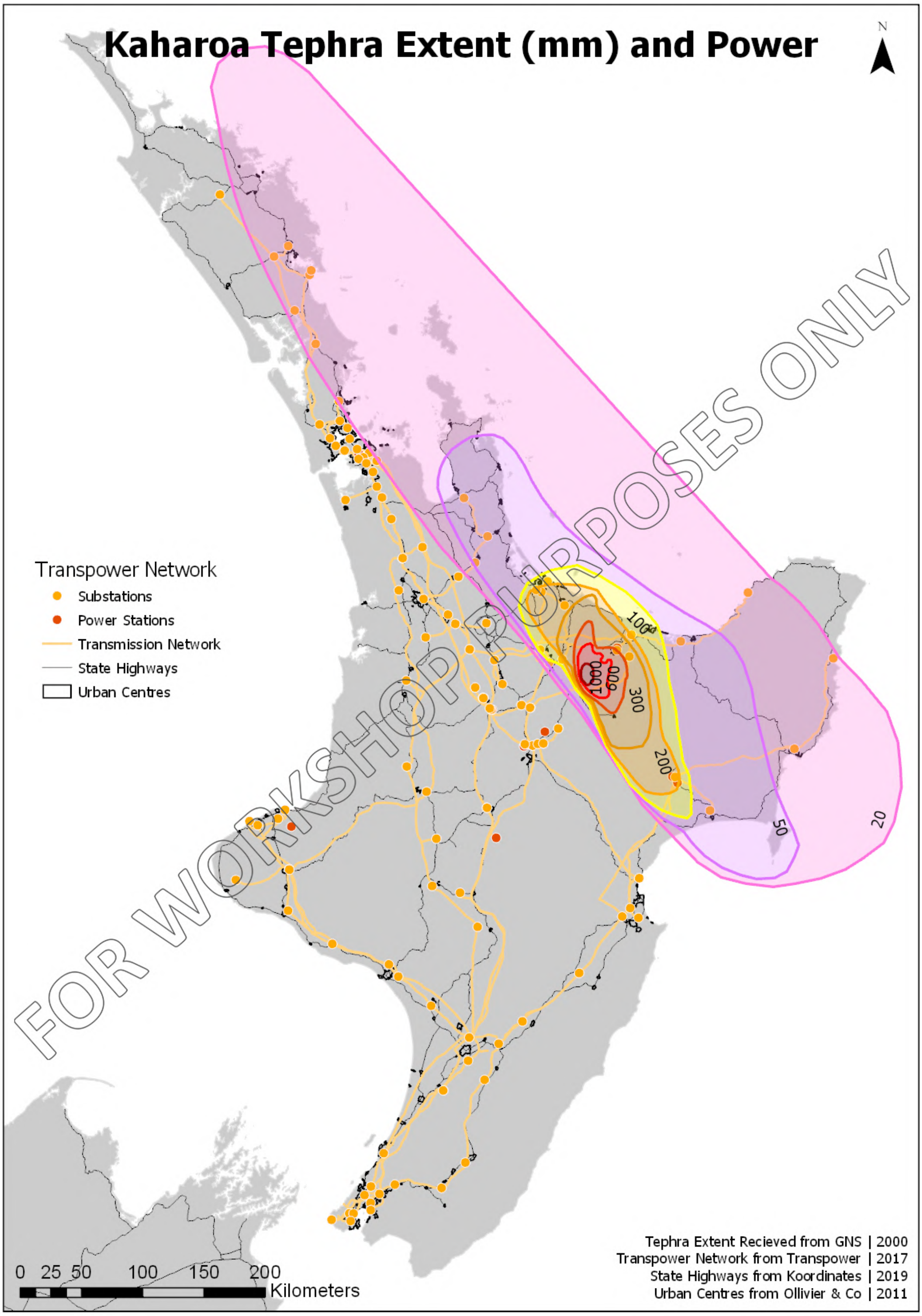
BUILDING IMPACTS FROM ASH FALL						
Ash Thickness **(mm)**	Total	Residential	Commercial	Education	Hospital	Civil Defence
>3,000	4	0	0	0	0	0
1,000	203	56	0	3	0	0
600	5,684	3,155	14	48	0	0
300	10,008	4,333	19	42	2	0
200	39,129	22,875	123	39	29	0
100	72,810	45,538	735	271	52	0
50	92,766	49,624	603	200	62	2
20	198,418	124,141	1,891	1,075	67	0
Total exposed to ash fall	419,022	249,722	3,385	1,678	212	2

Appendix Table B.6: 1314 AD Kaharoa Eruption scenario ash fall impact on agricultural farms and livestock from the ESDW impacts poster in Figure B.7. Listed in total number of assets exposed to ash fall.

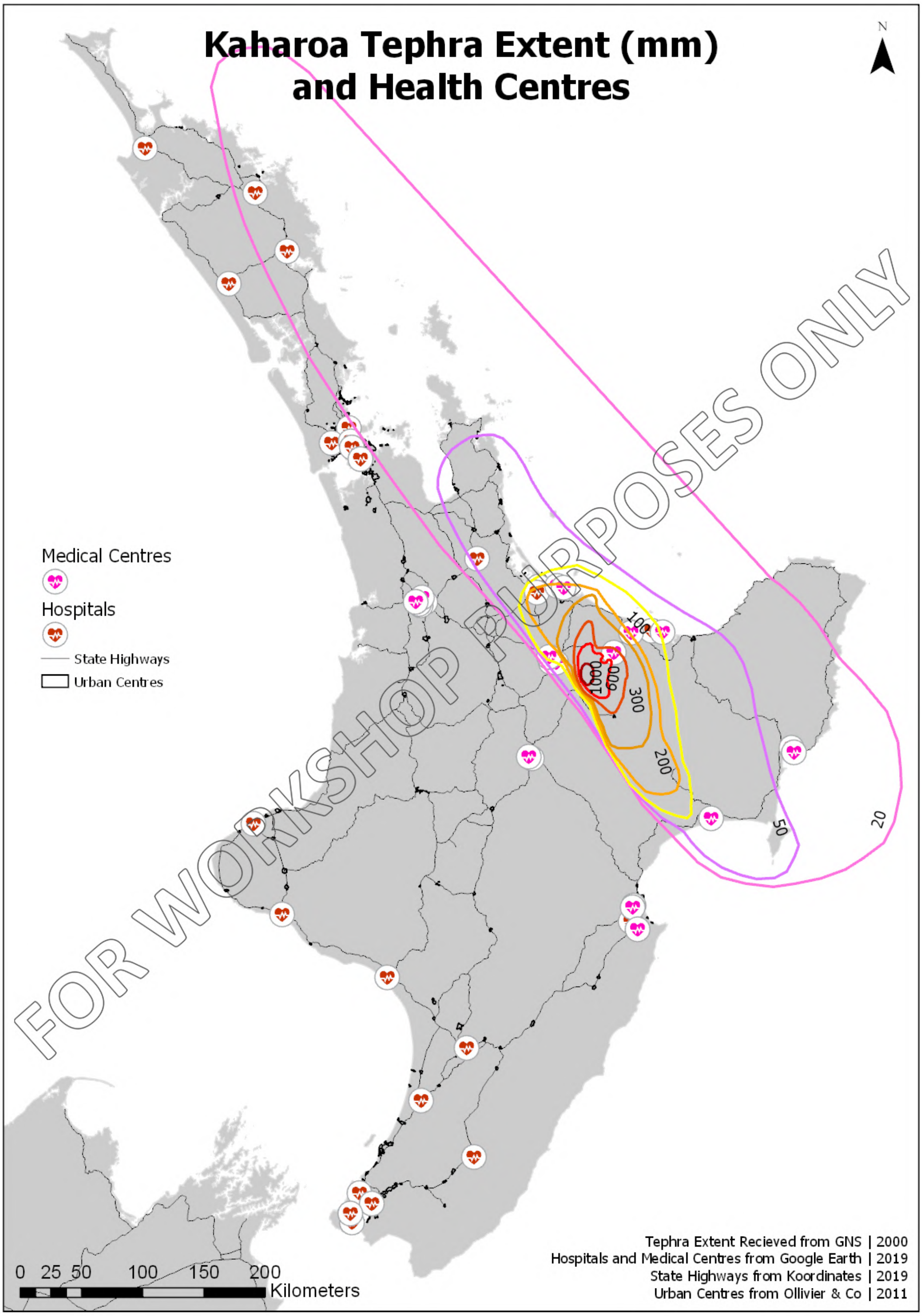
AGRICULTURAL IMPACTS FROM ASH FALL	
Farms exposed to Kaharoa ash fall:	
Pastoral	35,630
Horticultural	5,782
Livestock exposed to Kaharoa ash fall:	
Sheep	17,479,454
Beef Cattle	4,124,082
Dairy Cattle	2,923,091



Appendix Figure B.8: 1314 AD Kaharoa Eruption isopach with transport lines and locations overlaid.



Appendix Figure B.9: 1314 AD Kaharoa Eruption isopach with the Transpower network lines overlaid.



Appendix Figure B.10: 1314 AD Kaharoa Eruption isopach with hospitals and medical centres locations overlaid.

Appendix Table B.7: The optional qualitative hazard scenarios provided to the four "jig-sawed" groups in Exercise Three of the ESDW

Scenario Combination	Group Assigned	Pre-Eruption (unrest)		Syn-Eruption			Post-Eruption
		Time	**Episodicity**	**Geographic Location**	**Time**	**Magnitude**	**Time**
Combo 1	**Three**	Long	Steady	Unknown	Short	Small	Long
Combo 2	**One**	Short	Steady	Known	Long	Moderate	Short
Combo 3	**Four**	Rapid onset	Rapid onset	Known	Long	Very Large	Long
Combo 4	**Two**	Long	Sporadic	Known	No Eruption		-

Appendix Table B.8: The optional qualitative impact scenarios provided to the four "jig-sawed" groups in Exercise Three of the ESDW.

Scenario Combination	Group Assigned	Impacts and Consequences
Combo 1	**Two**	**Pre-Eruption:** Prolonged social anxiety from 'unrest' informed by natural cues. Risk perception decreases and low trust follows. **Syn-Eruption:** eruption does occur.
Combo 2	**Three**	**Syn-Eruption:** Lahars down the Waikato River causing cascading damage and disruptions of all hydro-electric power generation. Ash fall also covers ~500km of transmission line and 8 GXPs (only Taranaki HV line working) causing a deficiency of power to Auckland City. Taupō town is destroyed. **Post-Eruption:** Lahars down the Waikato River, impact on transport (roads, rail etc.) downstream.
Combo 3	**One**	**Syn-/Post Eruption:** Daily ash events across the North Island during springtime causing: - Aviation issues (incl. weekly ash at Auckland Airport). - Around 1,000 pastoral farms are non-functional. - Horticulture germination and flowering is effect, around 500 Bay of Plenty farms impacted. - Sporadic power issues due to ash loading.
Combo 4	**Four**	**Pre-Eruption:** 'Unrest' drives concern about magma beneath Taupō town causing complex evacuation measures. **Syn-Eruption:** Tsunami is triggered in Lake Taupō that severely impacts Turangi.

B.3 ECLIPSE SCENARIO DEVELOPMENT WORKSHOP DATA

Appendix Table B.9: ECLIPSE Scenario Development Workshop data from March 25th 2019. The "Domain" and "Node" columns relate to Figure 2.1 in *Chapter 2* where domain describes whether the group and/or statement from the group sit within the Policy or Science domains and where the node describes what specific interest the groups' statement strongly relates to. This was done early within the research project to help guide the research in credible and relevant directions.

Workshop Group	Workshop Activity	Discussion / Comments	Domain	Node	Broad Theme	Group Questions	Workshop Questions
CDEM	Exercise One	Decision-making.	Policy	Applied Science	Decision-making	How will we use them?	Use
CDEM	Exercise One	Public education and messaging.	Policy	Simple Information	Public Information and Education	How will we use them?	Use
CDEM	Exercise One	Contingency Planning.	Policy	Applied Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Reducing uncertainty (or increasing?).	Policy	Simple Information	Decision-making	How will we use them?	Use
CDEM	Exercise One	Guide development of templates: identifying vulnerable communities.	Policy	Applied Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Consistent messaging.	Policy	Simple Information	Public Information and Education	How will we use them?	Use
CDEM	Exercise One	Warning systems.	Policy	Real Time	Utility of Scenarios	How will we use them?	Use
CDEM	Exercise One	Recovery planning: economic impacts, social impacts, built environment.	Policy	Applied Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Exercise and planning.	Policy	Applied Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Training modules.	Policy	Applied Science	Utility of scenarios	How will we use them?	Use

CDEM	Exercise One	Land use planning.	Policy	Applied Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Response planning (can't write for every scenario but identify themes, common issues): use credible, all levels, multiple opinions (based on likelihood, alternate scenarios).	Science	Basic Science	Planning and/or Policy	How will we use them?	Use
CDEM	Exercise One	Decision-tree process: development and visualisation of what's happening (identify triggers for action and engagement), dynamic adaptive pathways.	Policy	Inter-disciplinarity	Decision-making	How will we use them?	Use
CDEM	Exercise One	Educate and inform conversations with stakeholders.	Policy	Inter-disciplinarity	Public Information and Education	How will we use them?	Use
CDEM	Exercise One	Focus on hazards not 'event' to help distinguish from cone volcanoes.	Science	Basic Science	Hazard requirements	How will we use them?	Use
CDEM	Exercise One	Tsunami Example: Flood response planning e.g. useful and necessary, cyclone paths.			Utility of Scenarios	How will we use them?	Use
CDEM	Exercise One	Not numbers like e-10 - Not relatable/incomprehensible.	Policy	Simple Information	Public Information and Education	Factors?	Factors / Character
CDEM	Exercise One	Different levels of impact - Not all for scaremongering.	Policy	Simple Information	Public Information and Education	Factors?	Factors / Character
CDEM	Exercise One	Positive impacts as well as negative impacts - Explore.	Policy	Demand-driven	Public Information and Education	Factors?	Factors / Character
CDEM	Exercise One	Reasonable number of scenarios for science to be credible for.	Policy	Applied Science	Preferred Scenarios	Factors?	Factors / Character
CDEM	Exercise One	Ones that *will* be worth planning for e.g. not ones in lifetime.	Policy	Demand-driven	Planning and/or Policy	Factors?	Factors / Character

CDEM	Exercise One	More scenarios - Paths, modular.			Preferred Scenarios	Factors?	Factors / Character
CDEM	Exercise One	Scale of impact (regional to international).	Science	Basic Science	Impacts	Factors?	Factors / Character
CDEM	Exercise One	Plain English - Not too much jargon.	Policy	Simple Information	Public Information and Education	Factors?	Factors / Character
CDEM	Exercise One	Different contexts (hydrothermal, Rotorua).	Policy	Demand-driven	Preferred Scenarios	Factors?	Factors / Character
CDEM	Exercise One	Impacts of unrest - Deformation, physical impacts to empower multiple impacts (e.g. economic, psychosocial, infrastructure.	Policy	Simple Information	Impacts	Factors?	Factors / Character
CDEM	Exercise One	Where they sit in terms of likelihood and consequences to set context when applying (qualitatively) - Matrix.	Policy	Applied Science	Decision-making	Factors?	Factors / Character
CDEM	Exercise One	Cartoons, games (PhD).	Policy	Simple Information	Public Information and Education	Formats?	Format
CDEM	Exercise One	DEVORA video, visual model (like AF8) but consider full impacts.	Policy	Simple Information	Impacts	Formats?	Format
CDEM	Exercise One	Useable in different contexts.	Policy	Demand-driven	Public Information and Education	Formats?	Format
CDEM	Exercise One	Something scalable for public/school presentation.	Policy	Simple Information	Public Information and Education	Formats?	Format
CDEM	Exercise One	Science-based decision trees but also jargon-free explanations - analogies are useful!	Policy	Simple Information	Utility of scenarios	Formats?	Format
CDEM	Exercise One	Meaningful real world examples without making irrelevant (e.g. Ruapehu/Tarawera),	Policy	Simple Information	Public Information and Education	Formats?	Format

		PowerPoint photos of real events (Chaiten).					
CDEM	Exercise Two	Community impacts a real focus, people first (animals are on there but people are not).	Policy	Demand-driven	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	1800 days' not useful	Policy	Simple Information		Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Tephra' - use of jargon.	Policy	Simple Information		Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Impacts throughout scenario not just at end - link to each stage.	Policy	Real Time	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Blue to show the PDC on lake which is blue, not easily grasped as hazard.	Policy	Simple Information		Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Impacts: what is the impact of that ash fall and exposure (so what?). Cues even if not lots of detail.	Policy	Simple Information	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Ash fall posters are good; maybe scenario posters.			Preferred Scenarios	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Put in context of recovery.	Policy	Applied Science	Planning and/or Policy	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Impact-based actions and suggested.	Policy	Inter-disciplinarity	Planning and/or Policy	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Significance of type of ash and how affects the general ash impacts.	Policy	Applied Science	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Needs to be scalable.	Policy	Simple Information	Preferred Scenarios	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Systematic interrelationships for impacts.	Policy	Inter-disciplinarity	Impacts	Kaharoa Example Scenario	Scenario Critique

CDEM	Exercise Two	Something like MMI index for impacts.	Policy	Simple Information	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Cultural significance of the area and how it relates to indigenous korero and lands.	Policy	Inter-disciplinarity	Decision-making	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Impact of loss A/C and other household essentials.	Policy	Demand-driven	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	What are GNS and MCDEM doing along the stages of the timeline.	Policy	Inter-disciplinarity	Planning and/or Policy	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	GIS files for integration into RiskScape	Policy	Demand-driven	Utility of Scenarios	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Linked transparently with other models (e.g. what weather in place?)	Policy	Inter-disciplinarity	Utility of Scenarios	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Process in timeline not linked to the map / locations - WHERE	Policy	Real Time		Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Path choosing games - Maori cartoon series.	Policy	Applied Science	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	What typically comes before or after a dome: how to prepare.	Policy	Simple Information	Planning and/or Policy	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Ability to 'play it out' visually through time.	Policy	Real Time	Decision-making	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Good that it covers multiple hazards but not enough detail about each.	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Different languages - including Te Reo Māori.	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique

CDEM	Exercise Two	Maybe group hazards by consequence and process (air fall - tephra/ballistics, slows -).	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Run scenario through different communities…support for	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Too small to read and see detail, scale not very clear/hard to see.	Policy			Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Tsunami: Lake volcanogenic tsunami and how different to oceanic tsunami.	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Not super friendly to public education applications.	Policy	Applied Science	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Duration of events happening at time X not crystal clear.	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	People / population and different levels of impact (e.g. different).	Policy	Applied Science	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Infrastructure loss to populations.	Policy	Demand-driven	Impacts	Kaharoa Example Scenario	Scenario Critique
CDEM	Exercise Two	Storytelling would help contextualise (e.g. family living here impacted in this way by…)	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
GeoNet	Exercise One	Exercise GHA7, volcano and communications/PIMs.			Public Information and Education	Use	Use
GeoNet	Exercise One	Source for communications and outreach	Policy	Simple Information	Public Information and Education	Use	Use
GeoNet	Exercise One	Frame volcano systems model discussions.	Science	Disciplinarity		Use	Use
GeoNet	Exercise One	Support and test vent and hazard mapping applications.	Science	Quality Assessment	Utility of Scenarios	Use	Use
GeoNet	Exercise One	Test the loss of nodes in the monitoring, network: Designing	Science	Quality Assessment	Utility of Scenarios	Use	Use

		monitoring, networks and regimes, detectability and interpretability modelling.					
GeoNet	Exercise One	All hazards and major infrastructure/social impacts across scenarios.	Policy	Inter-disciplinarity	Hazard Requirements / Impacts	Character	Factors / Character
GeoNet	Exercise One	Societal Behaviour: social media use and general media.	Policy	Simple Information	Public Information and Education	Character	Factors / Character
GeoNet	Exercise One	Deformation: location and scale: detectability	Science	Basic Science	Hazard Requirements	Character	Factors / Character
GeoNet	Exercise One	Enough science detail to provide size of impact (e.g. mm of deformation)	Science	Basic Science	Hazard Requirements / Impacts	Character	Factors / Character
GeoNet	Exercise One	Good timeline: multi-parameter	Science	Basic Science	Preferred Scenarios	Character	Factors / Character
GeoNet	Exercise One	Earthquake: MM7 duration (not wave forms, precise locations)	Science	Basic Science	Hazard requirements	Character	Factors / Character
GeoNet	Exercise One	Simulated/borrowed footage	Policy	Simple Information	Public Information and Education	Character	Factors / Character
GeoNet	Exercise One	Need to allow plans, injects and exercise to be written (exercise control document)	Policy	Applied Science	Planning and/or Policy	Character	Factors / Character
GeoNet	Exercise One	Clarify link to underpinning science behind any assumptions	Science	Basic Science	Credibility	Character	Factors / Character
GeoNet	Exercise One	Day and season agnostic? Mostly 7 but Christmas??	Science	Long Term	Preferred Scenarios	Character	Factors / Character
GeoNet	Exercise One	Gas/Geothermal: concentrations and locations (dispersion model).	Science	Basic Science	Hazard Requirements	Character	Factors / Character
GeoNet	Exercise One	Report with tables and details (PDF): succinct	Science		Preferred Scenarios	Delivery	Format
GeoNet	Exercise One	Shapefiles, KML, and maps that are images that can be cut and paste (links to previous point)			Preferred Scenarios	Delivery	Format

GeoNet	Exercise One	Metadata: files consistently named, non-confusing, easy-to-find files				Delivery	Format
GeoNet	Exercise One	Names as well as numbers (letters): versions, dates, latest-version-source-address				Delivery	Format
GeoNet	Exercise One	Discoverable in the final ECLIPSE web resources	Policy	Simple Information	Public Information and Education	Delivery	Format
GeoNet	Exercise One	Table: multi-parameter vs. multi-sector.	Science	Uncertain, Complex Information	Preferred Scenarios	Delivery	Format
GeoNet	Exercise One	Link to injects and exercise control.	Policy	Applied Science	Planning and/or Policy	Delivery	Format
GeoNet	Exercise One	Animation and graphics (for communications).	Policy	Simple Information	Public Information and Education	Delivery	Format
GeoNet	Exercise Two	Timeline with unrest *and* eruption	Science	Basic Science	Preferred Scenarios	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Impact metrics	Science	Basic Science	Impacts	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Single summary observations column is a win	Policy	Simple Information	Preferred Scenarios	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Road network reference	Policy	Simple Information	Impacts	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Shaded relief	Science	Basic Science	Preferred Scenarios	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Clustering into summary sheets	Policy	Simple Information	Preferred Scenarios	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Change in wind direction	Science	Basic Science	Preferred Scenarios	Useful/Strengths	Scenario Critique
GeoNet	Exercise Two	Months and years for bigger time units (less precise at longer timelines) - What is -few hours?			Preferred Scenarios	Missing/Frustrating/ Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Timeline of impacts, percentage of buildings, as well as total	Policy	Real Time	Preferred Scenarios	Missing/Frustrating/ Annoying/Unnecessary/Bad	Scenario Critique

		numbers (need time-slices of maps)					
GeoNet	Exercise Two	Lahar is missing other catchments.	Science	Basic Science	Hazard Requirements	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	More detail in the eruption column(s). Tempo - ash fall timing.	Science	Basic Science	Hazard Requirements	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Multiple locations, unrest without eruption.	Policy	Demand-driven	Preferred Scenarios	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Detailed report behind those summaries (need time-slices of maps).	Science	Uncertain, Complex Information	Preferred Scenarios	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Earthquake maps.	Science	Basic Science	Hazard Requirements	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Max HIM points as well as totals.	Science	Basic Science	Hazard Requirements	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Monitoring networks and data on maps.	Science	Basic Science	Preferred Scenarios	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	VABs and VALs - Iterative with team as scenario written.	Science	Basic Science	Decision-making	Missing/Frustrating/Annoying/Unnecessary/Bad	Scenario Critique
GeoNet	Exercise Two	Synergy with near-real-time GeoNet impact forecasting.	Policy	real Time	Decision-making	Needs/Credibility/Opportunities/Improvements	Scenario Critique
GeoNet	Exercise Two	Link to additional reading. Mitigation, preparedness, resources.	Policy	Simple Information	Planning and/or Policy	Needs/Credibility/Opportunities/Improvements	Scenario Critique
GeoNet	Exercise Two	Expanded unrest science.	Science	Uncertain, Complex Information	Preferred Scenarios	Needs/Credibility/Opportunities/Improvements	Scenario Critique

GeoNet	Exercise Two	Duration of phenomena within each row.	Science	Basic Science	Hazard Requirements	Needs/Credibility/Opportunities/Improvements	Scenario Critique
GeoNet	Exercise Two	Footprints of all 10 hazards with *temporal* arrival and HIMs.	Science	Basic Science	Hazard Requirements	Needs/Credibility/Opportunities/Improvements	Scenario Critique
GeoNet	Exercise Two	InSAR and GPS deformation.	Science	Basic Science	Hazard Requirements	Needs/Credibility/Opportunities/Improvements	Scenario Critique
GeoNet	Exercise Two	Infrastructure and social impacts.	Policy	Applied Science	Impacts	Needs/Credibility/Opportunities/Improvements	Scenario Critique
Industry and Lifelines	Exercise One	Planning - Readiness & Reduction.	Policy	Applied Science	Planning and/or Policy	How would you use caldera eruption scenarios?	Use
Industry and Lifelines	Exercise One	What to do - Include more severe end of possible impacts, multi-region, summary.	Policy	Simple Information	Planning and/or Policy	How would you use caldera eruption scenarios?	Use
Industry and Lifelines	Exercise One	Cordon management? Access (when, who, why, how); livestock impact.	Policy	Demand-driven	Decision-making	How would you use caldera eruption scenarios?	Use
Industry and Lifelines	Exercise One	Understanding impacts important. Maintaining communication. Needs assessment.	Policy	Demand-driven	Planning and/or Policy	How would you use caldera eruption scenarios?	Use
Industry and Lifelines	Exercise One	Adaptable land use policies - Flexible/adjustable (EXPLORE THIS)	Policy	Applied Science	Planning and/or Policy	How would you use caldera eruption scenarios?	Use
Industry and Lifelines	Exercise One	Range would be useful - unrest, small event, medium eruption, big eruption; multi-hazard.	Policy	Demand-driven		What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Trigger points.	Science	Uncertain, Complex Information	Preferred Scenarios	What do the scenarios need to have to be useful?	Factors / Character

Industry and Lifelines	Exercise One	Scenarios need to consider (allow exploring) management and communications responses.	Policy	Real Time	Planning and/or Policy	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Unrest vs. eruption (distinct issue).	Science	Uncertain, Complex Information	Preferred Scenarios	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Holistic integrated recovery plans.	Policy	Applied Science	Planning and/or Policy	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Animal welfare (ash fall) = instant and widespread. Will be huge demand; water supplies (earthquake impact, blockage), evacuation (?), emergency feed, change in land use (?).	Policy	Demand-driven	Impacts	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Loss of essential services important - seasonal variability. Power, road (inputs and outputs), communications.	Policy	Inter-disciplinarity	Impacts	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Ash impacts on machinery.	Policy	Simple Information	Impacts	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	What preparedness activities can be done?	Policy	Simple Information	Planning and/or Policy	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Uncertainty of duration? What impact intensity? - Tipping points	Policy	Real Time	Preferred Scenarios	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Which hazard has the most impact? Lahar, ash fall.	Policy	Demand-driven	Impacts	What do the scenarios need to have to be useful?	Factors / Character
Industry and Lifelines	Exercise One	Accurate information on likely impacts and response/mitigation - pre-prepared.	Policy	Simple Information	Planning and/or Policy	What do the scenarios need to have to be useful?	Factors / Character

Industry and Lifelines	Exercise Two	Good to have spatial intelligence - footprint and intensity useful (where should the focus be?).	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Impacts not hazard - Animals, infrastructure, buildings (where should the focus be?).	Policy	Applied Science	Impacts	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Timeline of what occurs - Forecasting (preferred, likelihood of future) vs. prescriptive: event tree approach would be useful.	Policy	Demand-driven	Decision-making	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Scenarios…would be useful to test management decision - Factors which influence major issues/priorities, local vs. national priorities.	Policy	Applied Science	Decision-making	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Impact states (sever, moderate, low - Priority). High priority e.g. Dairy vs. Sheep - When will this erupt? How long will it erupt for?	Policy	Real Time	Impacts	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Type of ash? Where ash is going next (rainfall)?	Policy	Simple Information	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Plain language (what happening, why worry?).	Policy	Simple Information	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Easy to read format.	Policy	Simple Information	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	How will it affect us?	Policy	Simple Information	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Industry and Lifelines	Exercise Two	Time of year.	Policy	Simple Information	Preferred Scenarios	Kaharoa Example Scenario	Scenario Critique

Industry and Lifelines	Exercise Two	Statistics New Zealand - Population demographic of whole area, including rural and rural township, employment, ethnicity.	Policy	Demand-driven	Decision-making	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise One	As soon as we get into a rest period 'He Tohu?' (What's up?).	Policy	Timely Process	Decision-making	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Environmental trigger for the social (and political stuff - and a spiritual thing). Holistic, crosses across multiple domains.	Policy	Timely Process	Preferred Scenarios	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	During a period of unrest - Quite a reluctance for Tangata Whenua to evacuate.	Policy	Demand-driven		How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	2009 - took a lot of convincing to get people to evacuate - Forced evacuation vs. self-evacuating.	Policy	Demand-driven		How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	People won't evacuate unless there's a certainty that the whenua will still be there.	Policy	Simple Information	Decision-making	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Trigger for whole community meeting - Everybody is getting the same message.	Policy	Demand-driven	Planning and/or Policy	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Early notification, engagement, developed from within - No matter what.	Policy	Inter-disciplinarity	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use

Iwi	Exercise One	Embedded into school curriculum - Whanau centred - Like power-up model.	Policy	Applied Science	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	If you have a good recovery policy it's easier to bounce back.	Policy	Timely Process	Planning and/or Policy	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	If people leave they will follow their whakapapa lines (which may be immediate neighbours) - Concept of home; everything it stands for.	Policy	Real Time		How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Life threatening - Went into a state of karakia (prayers).	Policy	Real Time	Impacts	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	The mountain won't harm me because I've lived here forever (this could be problematic).	Policy	Demand-driven		How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Trust' in scientists and 'authorities'.	Policy	Demand-driven	Decision-making	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Autonomy and self-organise.	Policy	Demand-driven	Planning and/or Policy	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Reciprocity and continuous feedback.	Policy	Inter-disciplinarity	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use

Iwi	Exercise One	Stories - Recent, past, overseas including experience.	Policy	Real Time	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Opportunity every 3-4months to discuss progress updates.	Policy	Inter-disciplinarity	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Cultural connotations of language - Away from negative e.g. hazard management .	Policy	Applied Science	Public Information and Education	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Natural phenomena vs. hazard management.	Policy	Applied Science	Hazard Requirements	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise One	Scenario development - Monitoring, engagement, preparedness, ongoing iterative process.	Policy	Inter-disciplinarity	Planning and/or Policy	How might you use caldera scenarios (in your current role)?	Use
Iwi	Exercise Two	Timescales - Response/discussion triggers at different time points.	Policy	Inter-disciplinarity	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Purakau and stories of population movement - To link. Look at Sylvia's example for how to get people to connect to the information - Clickable waiata.	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Interactive maps with video examples - impact of ash fall: Tarawera ash fall before and after photos/overseas examples	Policy	Applied Science	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Humanise the impacts - Roads = relationships.	Policy	Demand-driven	Public Information and Education	Kaharoa Example Scenario	Scenario Critique

Iwi	Exercise Two	Not wanting to scare people too much.	Policy	Demand-driven	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	We love maps.	Policy	Applied Science	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Language is a bit 'out the gate'.	Policy	Simple Information	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Water supply - Land, rivers, animals poisoned - Kai from other centres.	Policy	Demand-driven	Impacts	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Kinship ties – Ngāti Tūwahretoa, Te Arawa – Marae.	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	More than health centres - Civil Defence centres, Marae.	Policy	Simple Information	Preferred Scenarios	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	In a GIS - Someone guiding through the information, selectable layers.	Policy	Demand-driven	Hazard Requirements	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	How do we cater to different people? Different learning types.	Policy	Inter-disciplinarity	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Accessibility of data/wifi.	Policy	Timely Process	Preferred Scenarios	Kaharoa Example Scenario	Scenario Critique
Iwi	Exercise Two	Photos/images where you can see yourself in them/relate.	Policy	Simple Information	Public Information and Education	Kaharoa Example Scenario	Scenario Critique
Research Scientists	Exercise One	To define parameters to help make calls (what information is needed).	Policy	Demand-driven	Decision-making	How could you use them?	Use
Research Scientists	Exercise One	Know what we need to develop (e.g. Better understanding of timescales and processes).	Policy	Demand-driven	Hazard Requirements	How could you use them?	Use
Research Scientists	Exercise One	Define decision-making thresholds.	Policy	Demand-driven	Decision-making	How could you use them?	Use
Research Scientists	Exercise One	Real-time response (eventually).	Policy	Real Time	Preferred Scenarios	How could you use them?	Use

Research Scientists	Exercise One	Be flexible (general for Okataina vs. Taupo) - On short time scales.	Science	Basic Science	Preferred Scenarios	What should they have?	Factors / Character
Research Scientists	Exercise One	Two-ways e.g. reversible from one end to the other.	Science	Basic Science	Preferred Scenarios	What should they have?	Factors / Character
Research Scientists	Exercise One	Be bullet-proof to avoid confusion/false alarms. Seamless model to estimate unrest to eruption.	Science	Quality Assessment	Decision-making	What should they have?	Factors / Character
Research Scientists	Exercise One	Response to data coming in real-time (eventually).	Policy	Real Time	Preferred Scenarios	What should they have?	Factors / Character
Research Scientists	Exercise One	Has to be centralised (if poorly developed) for decision makers. But not public? -Separate interface?	Science	Disciplinarity	Planning and/or Policy / Public Information and Education	How should they be available?	Format
Research Scientists	Exercise Two	Limited use as it is a red eruption (rigid form, if it happened again on any day it would be different).			Decision-making	Is it useful? How?	Scenario Critique
Research Scientists	Exercise Two	Good for triggering thoughts on what needed.	Policy	Demand-driven	Utility of Scenarios	Is it useful? How?	Scenario Critique
Research Scientists	Exercise Two	Isopach maps start at 20mm! Need to look down to 0.1mm for impacts.	Science	Basic Science	Hazard Requirements	Frustrations?	Scenario Critique
Research Scientists	Exercise Two	Very specific timescales.	Science	Uncertain, Complex Information	Hazard Requirements	Frustrations?	Scenario Critique
Research Scientists	Exercise Two	Not all thing should be linked to volcano, e.g. Tectonic earthquakes e.g. Mammoth.	Science	Uncertain, Complex Information	Hazard Requirements	Frustrations?	Scenario Critique
Research Scientists	Exercise Two	Living scenario capability.	Science	Long Term	preferred scenarios	Missing?	Scenario Critique
Research Scientists	Exercise Two	Eruption inevitable' point.	Science	Uncertain, Complex Information	Hazard Requirements	Missing?	Scenario Critique

Research Scientists	Exercise Two	Some percentage chances, timeframes, windows, (where is tipping point?) e.g. Rabaul eruption.	Science	Uncertain, Complex Information	Decision-making	Missing?	Scenario Critique
Group One	Exercise Three	Testing/training.	Policy	Applied Science	Utility of Scenarios	Most important potential uses or applications?	Use
Group One	Exercise Three	Community resilience/training.	Policy	Applied Science	Public Information and Education	Most important potential uses or applications?	Use
Group One	Exercise Three	Saving people's lives.	Policy	Real Time	Utility of Scenarios	Most important potential uses or applications?	Use
Group One	Exercise Three	Better educated/definition of the problem.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group One	Exercise Three	Autonomy in planning response to scenario (we can't change the disaster scenario but we have autonomy on how we can plan for it as a community).	Policy	Inter-disciplinarity	Planning and/or Policy	Most important potential uses or applications?	Use
Group One	Exercise Three	Enabling adaptable response/better connected communities to information.	Policy	Applied Science	Utility of Scenarios / Public Information and Education	Most important potential uses or applications?	Use
Group One	Exercise Three	Credible scenario that people can relate to.	Policy	Demand-driven	Public Information and Education	Most important potential uses or applications?	Use
Group One	Exercise Three	discoverability of information/easier access	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group One	Exercise Three	Three credible sources needed.	Science	Basic Science	Preferred Scenarios	Most important potential uses or applications?	Use
Group One	Exercise Three	Pushing out information from a range of sources (farmers news, local councils etc.)	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use

Group One	Exercise Three	Scaremongering.			Public Information and Education	Tricky/challenging situations	Use
Group One	Exercise Three	Uncertainty, infrastructure, livestock.	Science	Uncertain, Complex Information	Decision-making	Tricky/challenging situations	Use
Group One	Exercise Three	Inter-regional networks/resources.	Policy	Inter-disciplinarity	Planning and/or Policy	Tricky/challenging situations	Use
Group One	Exercise Three	Scalable events that are manageable.	Policy	Demand-driven	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group One	Exercise Three	Credibility.	Science	Quality Assessment	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group One	Exercise Three	Relatable - Reduction of jargon (and acronyms).	Policy	Simple Information	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Humanise it.	Policy	Demand-driven	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Human health.	Policy	Demand-driven	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Agriculture.	Policy	Demand-driven	Public Information and Education	What do the scenarios need to have to be useful?	Factors / Character

						What do you need to know?	
Group Two	Exercise Three	Scenarios need to be realistic - 'somewhat test'	Science	Quality Assessment	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Timeframes - Accuracy, uncertainty.	Policy	Real Time	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Timely Information.	Policy	Timely Process	Utility of Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Continuous communications.	Policy	Inter-disciplinarity	Utility of Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	People in room don't hear it, they are on google.	Policy	Inter-disciplinarity	Public Information and Education	Tricky/challenging situations	Factors / Character
Group Two	Exercise Three	Building in realistic community response - People won't be lemmings.	Policy	Real Time	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Scenarios - Need to be developed within the NZ CDEM context and build off all the other previous work.	Policy	Applied Science	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character

Group Two	Exercise Three	Co-production - Needs to have users all contributing in their expertise, acknowledging all time poor.	Policy	Inter-disciplinarity	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Political Factors - Ministers…Mayors…	Policy	Demand-driven	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Everyone in same room getting the same story so they can make decision to self-evacuate.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group Two	Exercise Three	Co-production - Time poor, people can chip in as project develops, buy-in with involvement.	Policy	Inter-disciplinarity	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Social Media - One source of truth.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group Two	Exercise Three	Include social media in the scenario - Realistic	Policy	Inter-disciplinarity	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Co-production - Trigger points	Policy	Demand-driven	preferred scenarios / hazard requirements	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Relating the scenarios to people - Humanise it, e.g. Relating it to stories (Iwi). Different ethnicities.	Policy	Applied Science	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character

Group Two	Exercise Three	MUST BE: Plain language, understandable, e.g. Volunteer group, average reading age of a farmer - 12yr.	Policy	Simple Information	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Format
Group Two	Exercise Three	Seed scenarios: to allow other work with the develop eg. Play centres, schools. Needs tools to support. Empower to get them running.	Policy	Demand-driven	Public Information and Education	Most important potential uses or applications?	Format
Group Two	Exercise Three	Modular nature of framework: being able to change quickly, event tree??	Policy	Real Time / Timely Process	preferred scenarios	Most important potential uses or applications?	Format
Group Two	Exercise Three	Frustrations/Challenge: Public doesn't listen, how to get them to listen?	Policy	Demand-driven	Public Information and Education	Tricky/challenging situations	Use
Group Two	Exercise Three	Adding human stories to make scenarios real.	Policy	Inter-disciplinarity	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Testable Scenarios.	Policy	Applied Science	Preferred Scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	Scenarios which run through value chains, e.g. Dairy, Kiwifruit.	Policy	Demand-driven	Utility of Scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	Time, scalability and modular nature.	Policy	Demand-driven	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Two	Exercise Three	Iwi - Really input to build in Mātauranga Māori contribution to scenarios - Realism.	Policy	Inter-disciplinarity	Public Information and Education	What do the scenarios need to have to be useful?	Use

						What do you need to know?	
Group Two	Exercise Three	School level planning (education) - Scenario would be useful to play through these.	Policy	Demand-driven	Public Information and Education	Most important potential uses or applications?	Use
Group Two	Exercise Three	Scenarios would be useful as QA/QC management plans - Realistic, trigger points/tipping points. Decisions.	Policy	Demand-driven	Planning and/or Policy / Decision-making	Most important potential uses or applications?	Use
Group Two	Exercise Three	Pre-planning - Scenarios can be useful to play out something and pre-plan.	Policy	Demand-driven	Preferred Scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	Media and Communications.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group Two	Exercise Three	Want to identify loss of service for infrastructure.	Policy	Demand-driven	Utility of Scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	Pre-planning - Involving multiple agencies - Show how they fit in.	Policy	Inter-disciplinarity	preferred scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	CDEM - Explore the what-ifs - So if credible and realistic, play with it.	Science	Uncertain, Complex Information	Utility of Scenarios	Most important potential uses or applications?	Use
Group Two	Exercise Three	Understanding multi-hazard - Detailed scenario. Dynamic, adaptive pathway planning, need resource with it.	Science	Basic Science	Preferred Scenarios / Planning and/or Policy	Most important potential uses or applications?	Use
Group Two	Exercise Three	Small package that we can deliver to schools.	Policy	Demand-driven	Public Information and Education	Most important potential uses or applications?	Use
Group Three	Exercise Three	Public Education.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use

Group Three	Exercise Three	Planning - All 4R's.	Policy	Applied Science	Planning and/or Policy	Most important potential uses or applications?	Use
Group Three	Exercise Three	Communication.	Policy	Simple Information	Public Information and Education	Most important potential uses or applications?	Use
Group Three	Exercise Three	Gap analysis for physical science.	Science	Quality Assessment	Utility of Scenarios	Most important potential uses or applications?	Use
Group Three	Exercise Three	A scenario that comes and goes - Episodic.	Science	Basic Science	Preferred Scenarios	Tricky/challenging situations	Use
Group Three	Exercise Three	Political - 'So What?' Implications.	Policy	Inter-disciplinarity	Impacts	Tricky/challenging situations	Use
Group Three	Exercise Three	Applicable to wide range of people and cultures.	Policy	Inter-disciplinarity	Public Information and Education	Tricky/challenging situations	Use
Group Three	Exercise Three	Impacts - Phenomena (triggers and links) - Where to run away, when to come back?	Policy	Real Time	Impacts	Tricky/challenging situations	Use
Group Three	Exercise Three	Description of the uncertainty and how to express that - Include conversations relating to the uncertainty.	Science	Uncertain, Complex Information	Preferred Scenarios	Tricky/challenging situations	Use
Group Three	Exercise Three	The scenario relates to the customers language/'why' - Public, emergency management, lifelines etc. Handling animals within a cordon/area.	Policy	Simple Information	Public Information and Education	Tricky/challenging situations	Use
Group Three	Exercise Three	Dynamic adaptive pathway thinking - Multiple pathways.	Science	Uncertain, Complex Information	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character

Group Three	Exercise Three	Relatable to real experience - Historic and pre-historic.	Policy	Applied Science	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Three	Exercise Three	Able to be 'adapted' and flexible during an event - Real-time scenario	Policy	Real Time / Timely Process	Utility of Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Three	Exercise Three	Show the range of scenarios and maximum credible scenario - The 'go to'.	Policy	Demand-driven	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Four	Exercise Three	Prolonged unrest potentially easier because time to communicate and consider and plan.	Policy	Timely Process	Planning and/or Policy	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios
Group Four	Exercise Three	Rural support - Unrest; unrest, quick response necessary.	Policy	Demand-driven	Decision-making	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios
Group Four	Exercise Three	Focus is on event in CDEM and that's harder to constrain.	Policy	Demand-driven	Decision-making	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Rapid onset very dependent on time of day and week (e.g. Midnight).	Policy	Demand-driven	Preferred Scenarios	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios

Group Four	Exercise Three	Iwi used to rapid response - Skillset in rapid onset unrest, hangi etc. but relationships and protocols and tikanga not always clear. Slow onset - Time to consider and have conversations and planning.	Policy	Demand-driven	Planning and/or Policy	Tricky/challenging situations	Factors / Character
Group Four	Exercise Three	Farming recovery starts next day - Animals first.	Policy	Demand-driven	Decision-making	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Damage to cow sheds and supplies then act.	Policy	Demand-driven	Decision-making	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Four	Exercise Three	Uncertainty forces tough political conversations and there's more time for that in long unrest.	Policy	Timely Process	Public Information and Education	Tricky/challenging situations	Factors / Character
Group Four	Exercise Three	Access control' vs. 'cordon'.	Policy	Demand-driven	Decision-making	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Once eruption starts - This is an incident, need to deal with it.	Policy	Real Time	Decision-making	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Event-based response - Don't leave unless eruption evidence (Iwi, CDEM, rural) - But defining unrest/eruption; what is that point - Very hard (science).	Science	Uncertain, Complex Information	Planning and/or Policy / Hazard Requirements	Tricky/challenging situations	Factors / Character
Group Four	Exercise Three	Eruption more likely than not for trigger actions.	Policy	Real Time	Hazard Requirements	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Needs to consider rural and urban risks differently.	Policy	Demand-driven	Decision-making	Tricky/challenging situations	Factors / Character

Group Four	Exercise Three	Rapid onset forces focus on highest demand (e.g. Urban) so maybe not enough on rural communities.	Policy	Demand-driven	Decision-making	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios
Group Four	Exercise Three	Relationships building in advance.	Policy	Inter-disciplinarity	Public Information and Education	Most important potential uses or applications?	Use
Group Four	Exercise Three	Undertake response planning, evacuation, priorities, impacts.	Policy	Applied Science	Planning and/or Policy / Impacts	Most important potential uses or applications?	Use
Group Four	Exercise Three	Protocols in advance.	Policy	Applied Science	Public Information and Education	Most important potential uses or applications?	Use
Group Four	Exercise Three	How to manage rural vs. urban?	Policy	Inter-disciplinarity	Planning and/or Policy	Most important potential uses or applications?	Use
Group Four	Exercise Three	Communications Plans.	Policy	Applied Science	Planning and/or Policy	Most important potential uses or applications?	Use
Group Four	Exercise Three	Rapid onset to big eruption - Safety first.	Policy	Real Time	Planning and/or Policy	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios
Group Four	Exercise Three	Local knowledge of whenua and relationships.	Policy	Inter-disciplinarity	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Four	Exercise Three	Rapid onset - Will another one come? What's the cycle?	Science	Uncertain, Complex Information	Public Information and Education	What do the scenarios need to have to be useful? What do you need to know?	Qualitative Scenarios

Group Four	Exercise Three	Before send someone in - Life safety of response.	Policy	Demand-driven	Planning and/or Policy	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Loss of a 'pattern' compared to earthquakes, pre-, aftershocks.	Science	Uncertain, Complex Information	Hazard Requirements	What do the scenarios need to have to be useful? What do you need to know?	Factors / Character
Group Four	Exercise Three	What is likely to happen next? - Paths.	Science	Uncertain, Complex Information	Utility of Scenarios	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Impacts to distal tribe from Tarawera - e.g. Stories of experience from other hazards - legacy of Tarawera.	Policy	Applied Science	Impacts / Public Information and Education	Most important potential uses or applications?	Factors / Character
Group Four	Exercise Three	Reaching all people.	Policy	Inter-disciplinarity	Public Information and Education	Tricky/challenging situations	Use
Group Four	Exercise Three	How long for? Is the eruption over?	Science	Uncertain, Complex Information	Utility of Scenarios	Tricky/challenging situations	Use

Appendix C NZVSAP ECLIPSE Scenario Discussion Session

C.1 NZVSAP ECLIPSE Scenario Discussions Session Outline

The New Zealand Volcano Science Advisory Panel (NZVSAP) ESDS was part of an all-day NZVSAP Committee Meeting (*Table C.1*), held on the 21st August 2019 at the NEMA (formerly MCDEM) Bowen House in Wellington.

The ESDS opened with a presentation on what the ECLIPSE programme is, what scenarios are, and how they might be used. Participants were then asked to keep a series of questions in mind when presenters walked-through the ECLIPSE Scenario Framework (Version 1.2) and Scenario A. These questions were;

1. Are there any gaps or issues with the current approach [to the scenario framework and/or scenario]?
2. Will this [scenario framework and/or scenario] be useful for national level Civil Defence Emergency Management planning?
3. How could these scenarios help with your [the participants'] science objectives?

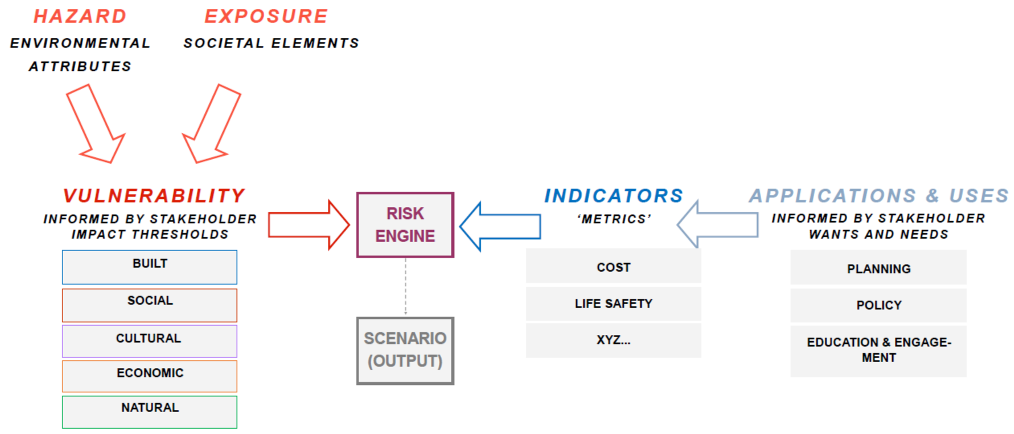
Participants were then asked to answer the questions individually and then brainstorm ideas and have a discussion as a group, of which the findings are detailed in *Chapter 3* and *Section C.3* below.

C.2 NZVSAP ECLIPSE Scenario Discussions Session Resources

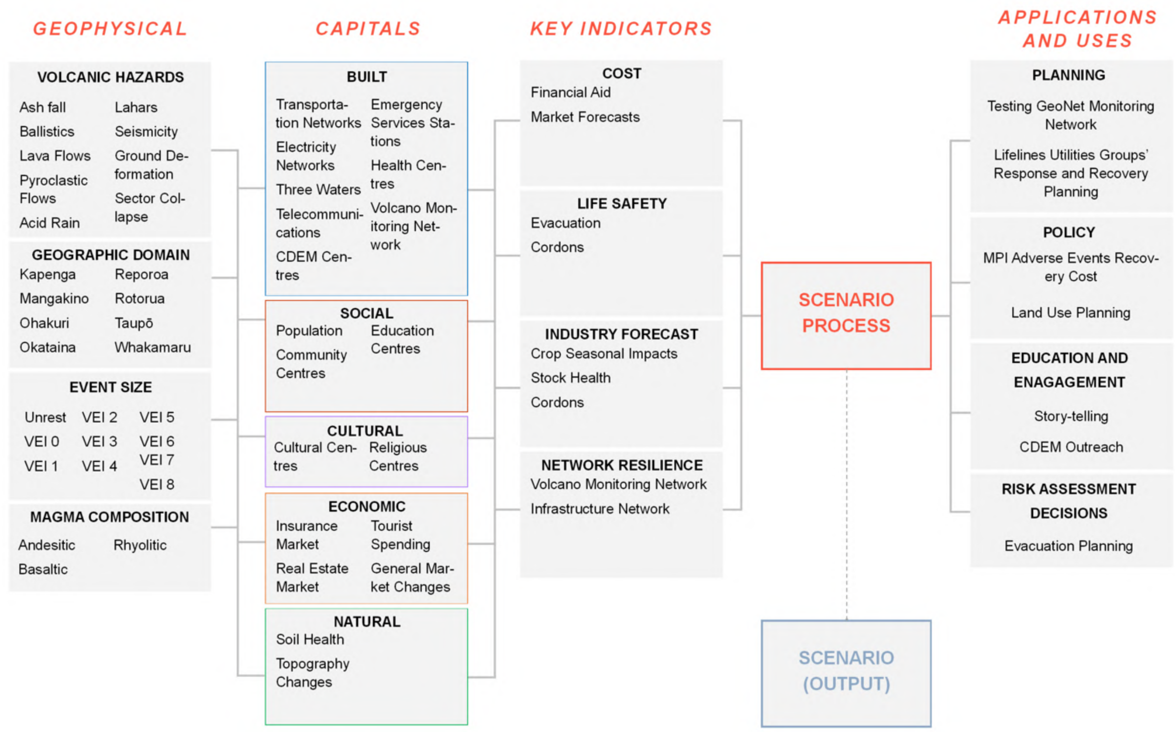
Appendix Table C.1: NZVSAP Committee Meeting Agenda.

TIME	ITEM	LEAD
	Morning Tea on arrival	
10:00-10:10	Welcome, housekeeping, and introductions.	Chair
10:10-11:45	New Zealand Guideline for Volcano Hazard Mapping.	Danielle Charlton/Graham Leonard
11:45-12:30	Hazard and Impact Scenario Development for Silicic Volcanoes in New Zealand.	Geena Campbell/Tom Wilson
12:30-13:00	***Lunch***	
13:00-13:50	Terms of Reference Update: Scientific Advice in an Emergency.	Chair
13:50-14:10	MetService satellite-based eruption detection and volcanic ash dispersion modelling.	Peter Kreft

14:10-14:30	Discussion on Consistent Messaging: Volcanic Activity and Geothermal Activity section updates.	Alistair Davies
14:30-14:40	Update on National Volcanic Risk Assessment Profile.	Chair
14:40-14:55	Any other business.	Chair
14:55-15:00	Confirm actions & wrap-up.	Chair



Appendix Figure C.1: ECLIPSE Scenario Framework Version 2.0 "Flow Chart of Framework" that was presented at the NZVSAP ESDS in August 2019.



Appendix Figure C.2: ECLIPSE Scenario Framework Version 1.2 "Base Framework" that was presented at the NZVSAP ESDS in August 2019.

C.3 NZVSAP ECLIPSE Scenario Discussions Session Data

Appendix Table C.2: NZVSAP ECLIPSE Scenario Discussion Session Data from August 21st 2019. The "Node" column relates to Figure 2.1 in Chapter 2 where node describes what specific interest the groups' statement strongly relates to. This was done within the research project to help guide the research in credible and relevant directions.

Workshop Group	Discussion / Comments	Node
Research Scientists	Event Size Box: Change to "Event Magnitude" as VEI measurements may not be the most beneficial.	Applied Science
Research Scientists	Temporal Aspect: Might be as easy as a time series of outputs as the situation and inputs changes.	Real Time
GeoNet / Research Scientists	Managing uncertainty.	Applied Science
GeoNet / Research Scientists	Communicating uncertainty.	Simple Information
Research Scientists	Link the uncertainty to network-based approaches to help better communicate it.	Inter-disciplinarity
Research Scientists	Network-based approaches to framework development, e.g. Event-Tree.	Inter-disciplinarity
Research Scientists	Ensure the ability to future proof the framework.	Real Time
Research Scientists	Allow sensitivity testing (also links to the network-based approach).	Inter-disciplinarity
GeoNet / NEMA / Research Scientists	Framework will need guidance on "how to use" – could use examples of maximum credible event scenario vs. other scenarios.	Applied Science
GeoNet / NEMA / Research Scientists	Possibly create a "choose-your-own-adventure" style guidance.	Simple Information
Research Scientists	Outputs.	Demand driven
NEMA / GeoNet	There are a limited number of societal actions/ranges at this phase/version (also links to the limitation on the temporal aspect too).	Inter-disciplinarity

Appendix D ECLIPSE Scenario Development Lifeline Utilities Workshop

D.1 ECLIPSE Scenario Development Lifeline Utilities Workshop Outline

The ECLIPSE Scenario Development Lifeline Utilities Workshop (ESDLUW) took place as part of the annual shared Waikato and Bay of Plenty Lifelines Forum (*Figure D.1*).

WAIKATO LIFELINE UTILITIES GROUP

BAY OF PLENTY LIFELINES GROUP

Waikato and Bay of Plenty Lifeline Utilities Forum

Thursday 22 August 2019 **Programme**

TIME	SESSION	SPEAKER
8:30	**Registration** – Exhibition Hall, Hamilton Gardens Pavilion, Hungerford Crescent, Cobham Drive, Hamilton East	
9:00	Mihi/Whakatau/Karakia	
9:10	Opening Address	**Hugh Vercoe** - WRC Councillor; Chair, Joint Committee
9:25	Waikato and Bay of Plenty Hazardscape *Emerging hazards for Lifeline Utilities*	**Rick Liefting** – Team Leader, Regional Resilience, ICM, WRC **Matthew Harrex** – Manager Planning and Development, Emergency Management, BOP
9:55	**Morning Tea**	
10:15	Digital Security During Incident Response *Preventing situations going from bad to worse*	**Jon Edney** – Security Specialist, Ultrafast Fibre, Hamilton
10:45	ECLIPSE Project - Workshop *Consider the potential impacts of volcanic unrest and how to manage this*	**Thomas Wilson PhD** - Associate Professor in Disaster Risk and Resilience, University of Canterbury
11:45	MCDEM Update *Update on what is happening at a National level for Lifeline Utilities*	**Ajay Makhija** - Senior Emergency Management Advisor, Ministry of Civil Defence & Emergency Management
12:00	**Lunch**	
12:50	Seismic Detection *Seismic detection system that quickly allows targeting of whether a building and structures need engineering inspection or not*	**Andrew Ball** - Technical Director of Structural Engineering, Beca, BOP
1:25	North Canterbury Transport Infrastructure Recovery (NCTIR) *Moving mountains to reconnect communities*	**Tresca Forrester** - Network Operations Manager NC Transport Infrastructure Recovery NZTA
1:55	Geospatial Update *Update on the increasingly important role that Geospatial (GIS) is playing in CDEM*	**Derek Phyn** - Senior Spatial Analyst | Spatial Analysis and Modelling, Science and Strategy, WRC
2:25	Radio as a Lifeline Utility *Building and maintaining resilience across the nation's public communication network*	**John Barr** - Communications Manager, Radio NZ
2:55	**Closing Address**	**Liam Ryan** – Waikato Lifeline Utilities Group Chair; System Optimisation, Journey Manager, NZTA

Appendix Figure D.1: Waikato and Bay of Plenty Lifelines Forum Agenda.

The workshop itself began with two introductory presentations (*Table D.1*) from presenters listed in *Table A#.2*. These presentations provided context on the ECLIPSE programme (*Section 1.1.1*), caldera risk in the Waikato and Bay of Plenty regions (*Chapter 1*), scenarios and their use (*Chapter 1*), and a walk-through of ECLIPSE Scenario B: Taupō Unrest Scenario (TUS) (*Chapter 4*).

Appendix Table D.1: Workshop specific agenda for the ESDLUW held on 22nd August 2019.

TASK	TIME ALLOCATED	CONTENT
Introductory Presentations	15 minutes	ECLIPSE programme. Taupō Volcanic Zone history. Aims and objectives of the workshop. Walk-through of Taupō Unrest Scenario.
Workshop Activity	30 minutes	Multi-disciplinary groups' brainstormed ideas and answers for question provided.
Feedback and Wrap-up	15 minutes	Each group reported back one idea/answer of importance. Where to next.

Appendix Table D.2: Presenters and facilitators of the ESDLUW and discussion, listed in order of presentation.

PRESENTER / FACILITATOR NAME	ROLE	ORGANISATION	TOPIC(S) PRESENTED
Brad Scott	Presenter / Facilitator	GNS Science, ECLIPSE	ECLIPSE programme. Taupō Volcanic Zone history, specifically Taupō Volcanic Centre's previous unrest episodes.
Geena Campbell	Presenter / Facilitator	University of Canterbury, ECLIPSE	Aims and objectives of the workshop. Walk-through of the Taupō unrest scenario (TUS). Facilitated feedback.
Daniel Blake	Facilitator	University of Canterbury	N/A
Kate Akers	Facilitator	Massey University, Joint Centre for Disaster Research	N/A

Following the introductory presentations, participants were asked to move into groups that consisted of representatives from various different organisations (listed in *Table A#.3* below). Ideally, this would result in one participant from each discipline in each group (e.g. one participant from a power provider, a telecommunications provider, CDEM, District Council, District Health Board (DHB) and so on). This was done, rather than having participants stay in discipline-based groups, to highlight how the response to an unrest event, like the TUS, would require communication and collaboration across multiple disciplines and organisations (Leonard et al., 2014; Gottsmann, Komorowski & Barclay, 2017).

Appendix Table D.3: Organisations that participated within the ESDLUW, listed by their related discipline categories.

DISCIPLINE GROUP	ORGANISATIONS IN ATTENDANCE
Civil Engineering	BECA Jacana Consulting Ltd.
District/City Councils	Hamilton City (HCC) Hauraki Matamata-Paiko Otorohanga Rotorua Lakes Taupō (TDC) Thames-Coromandel (Emergency Management) Waikato Waipa Western Bay of Plenty
District Health Boards	Bay of Plenty (BoP DHB) Lakes (Lakes DHB)
Fuel Providers	First Gas

	Mcfall Fuel
National Representatives	Department of Prime Minister and Cabinet (DPMC) National Emergency Management Agency (NEMA), formerly Ministry of Civil Defence and Emergency Management (MCDEM) New Zealand Lifelines Council
Power Providers	Counties Power Genesis Horizon Networks Mercury Powerco Transpower Unison Networks WEL Networks
Regional Councils	Bay of Plenty (Emergency Management) (BoPRC) Waikato (Joint Committee; GEMO) (WRC)
Science/Research	ECLIPSE GNS Science (GNS) Massey University (Joint Centre for Disaster Research; JCDR) University of Canterbury
Telecommunications Providers	Chorus Radio New Zealand (RadioNZ) Spark UltraFast Fibre
Transport Providers	New Zealand Transport Agency (NZTA)

	Port of Tauranga (PoT)

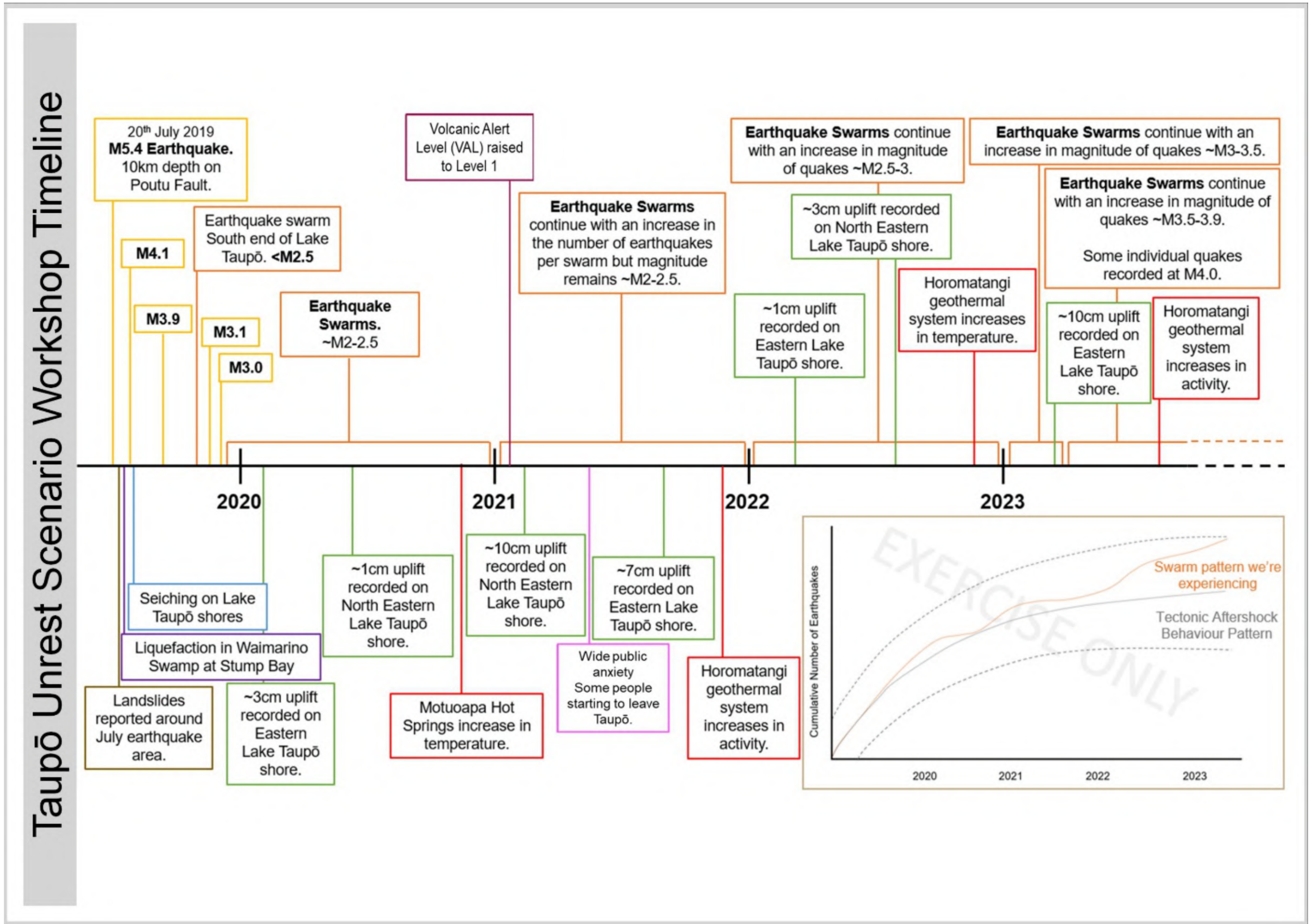
Once participants were in multi-disciplinary groups, they were provided with three broad questions to answer in response to the TUS;

- What would your organisations response to this scenario look like?
- What are the direct and indirect implications of a scenario like this to your organisation?
- What information would your organisation need to effectively respond to this scenario?

The goal was for participants to discuss how the impacts, and implications from these impacts, would affect their organisations, particularly from a long-term strategic planning perspective. Participants were given 30 minutes to brainstorm and list actions and ideas to these questions, which are collated and summarised in *Chapter 3* and *Appendix Section D.3*.

After the workshop activity, the research team facilitated 10 minutes of feedback. This involved going around each group and asking them to share, with all groups, what they felt was the most important or stand out issue, response, and/or action they had listed. This is collated and summarised in *Chapter 3* and *Appendix Section D.3*.

D.2 ECLIPSE Scenario Development Lifeline Utilities Workshop Resources



Appendix Figure D.2: Taupō Unrest Scenario timeline provided to participants in the ESDLUW.

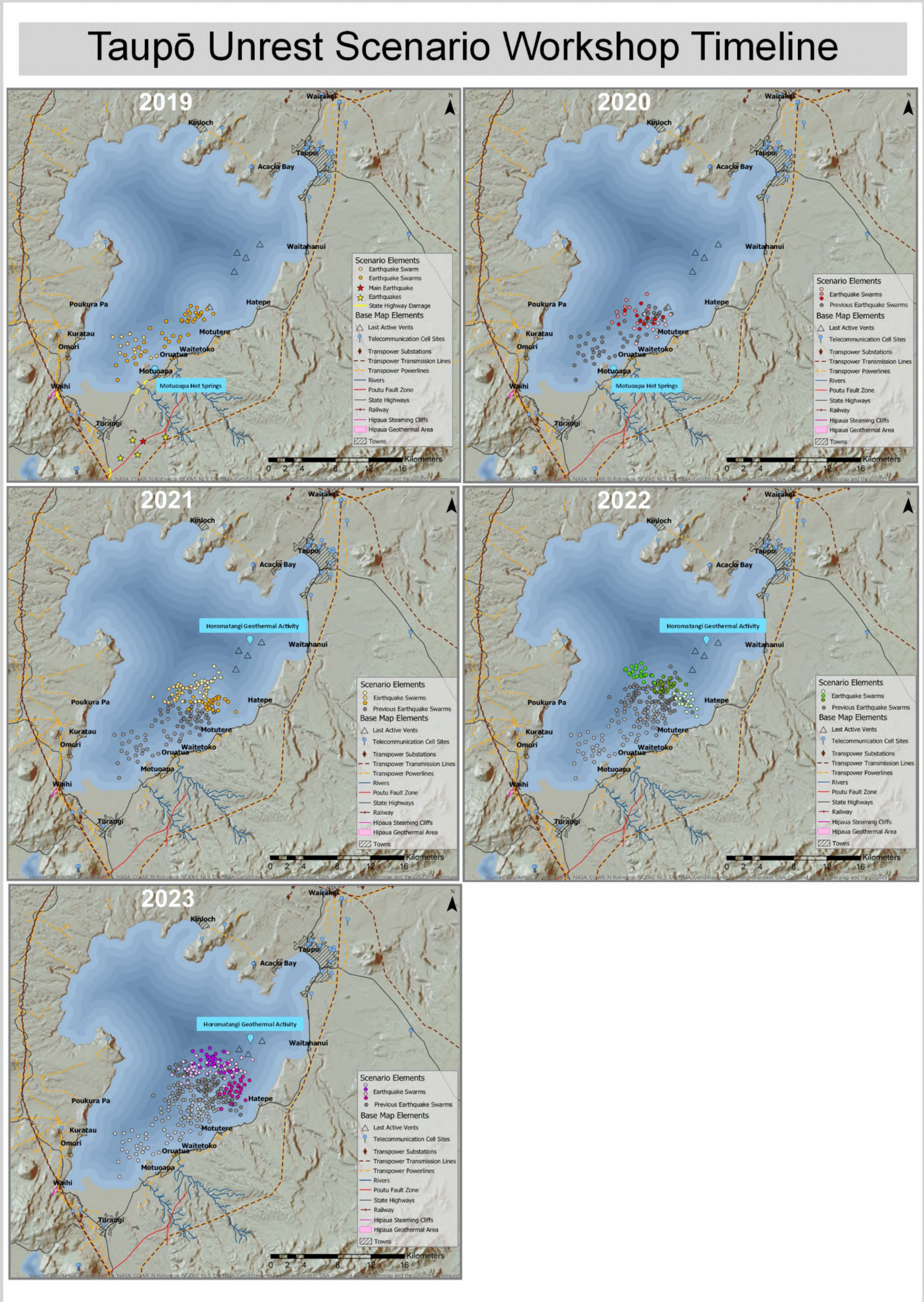
Taupō Unrest Scenario Workshop Questions

1. What would your organisations response to this scenario look like?

2. What are the direct and indirect implications of a scenario like this to your organisation?

3. What information would your organisation need to effectively respond to this scenario?

Appendix Figure D.3: Question sheet provided to participants in the ESDLUW.



Appendix Figure D.4: Taupō Unrest Scenario maps provided to participants in the ESDLUW.

D.3 ECLIPSE Scenario Development Lifeline Utilities Workshop Data

Appendix Table D.4: ECLIPSE Scenario Development Lifeline Utilities Workshop data from August 22nd 2019. The "Domain" and "Node" columns relate to Figure 2.1 in Chapter 2 where domain describes whether the groups' statement sits within the Policy or Science domains and where the node describes what specific interest the groups' statement strongly relates to. This was done throughout the research project to help guide the research in credible and relevant directions.

Workshop Group	Questions	Discussion / Comments	Domain	Boundary Node	Broad Theme
Group A	Question One	Plan for the worst	Policy	Applied Science	Planning/Preparedness
Group A	Question One	Make and practice plans (Business Continuity plans, BC plans, Evacuation plans, preparedness plans, security plans, fuel plans) within our own business and between agencies.	Policy	Inter-disciplinary	Planning/Preparedness
Group A	Question One	Good communications	Policy	Inter-disciplinary	Communications
Group A	Question One	How are we communicating as a lifeline utility, as DHB, as TA…?	Policy	Inter-disciplinary	Communications
Group A	Question One	Regular community meetings	Policy	Inter-disciplinary	Communications
Group A	Question One	Identify community leaders.	Policy	Inter-disciplinary	Communications
Group A	Question One	Mapping location of our own staff (all).	Science	Disciplinary	
Group A	Question One	Business continuity, if roading networks affected.	Science	Disciplinary	Critical Infrastructure
Group A	Question One	Plus, Health and Safety of own staff.	Policy	Demand-driven (consultancy)	Health
Group A	Question One	Trigger point about when CDEM emergency declared - pre-arranged/pre-understood protocols.	Science	Uncertain, complex information	Trigger Points
Group A	Question One	Long-term planning: potential shift of investments.	Science	Long Term	Planning/Preparedness
Group A	Question Two	Psychological impacts	Policy	Demand-driven (consultancy)	Health
Group A	Question Two	DHB: psychological issues.	Policy	Demand-driven (consultancy)	Health
Group A	Question Two	Voluntary migration for those who can leave	Policy	Real Time	Evacuation

Group A	Question Two	Those who can't leave (lower socio-economic groups) - possible increase in demand for DHB services.	Science	Supply-driven (autonomy)	Health
Group A	Question Two	Loss of supply with uplift and subsidence - power companies, also water/wastewater.	Policy	Applied Science	Critical Infrastructure
Group A	Question Two	Loss of all utilities.	Policy	Inter-disciplinary	Critical Infrastructure
Group A	Question Two	Access to community if roading network affected.	Policy	Timely Process	Critical Infrastructure
Group A	Question Two	Economic impact - regionally, nationally.	Policy	Demand-driven (consultancy)	Economic
Group A	Question Two	Investment in the town, in infrastructure, with no long-term uncertainty.	Policy	Demand-driven (consultancy)	Economic
Group A	Question Two	Emotional connection to place - people that don't want to leave but jobs impacted, communities impacted.	Science	Supply-driven (autonomy)	Evacuation
Group A	Question Two	Ashfall/Gas - contamination of water.	Science	Basic Science	Health
Group A	Question Three	Knowledge of prevailing winds.	Science	Basic Science	Hazard Information and Forecasts
Group A	Question Three	Lifeline interdependencies	Policy	Inter-disciplinary	Critical Infrastructure
Group A	Question Three	Location of; critical infrastructure, marae/gathering point of the community.	Policy	Inter-disciplinary	Critical Infrastructure
Group A	Question Three	Case studies of similar events worldwide including consequences on people and infrastructure.	Policy	Simple Information	Critical Infrastructure
Group A	Question Three	Plus authorities' actions and community response.	Policy	Simple Information	Response/Decisions
Group A	Question Three	What is going to happen? GNS crystal ball & area of impact.	Science	Uncertain, complex information	Hazard Information and Forecasts
Group A	Question Three	Trigger points for escalation and evacuation.	Science	Uncertain, complex information	Trigger Points
Group A	Question Three	Likelihood and consequences of decisions/actions e.g. evacuation.	Policy	Applied Science	Response/Decisions
Group A	Question Three	Knowledge of impacts e.g. make-up of gas, ash etc. and what is its impact on water/wastewater/people/stock/tsunami risks.	Science	Basic Science	Hazard Information and Forecasts

Group B	Question One	Identify affected parties.	Policy	Inter-disciplinary	
Group B	Question One	Gather information science data, including expert advice.	Policy	Simple Information	Hazard Information and Forecasts
Group B	Question One	Consider knock-on effects to other communities.	Policy	Inter-disciplinary	
Group B	Question One	Consider hydro-power.	Science	Disciplinary	Critical Infrastructure
Group B	Question One	Establish evacuation plans - Waikato (mystery creek) and neighbouring districts.	Policy	Applied Science	Scenarios
Group B	Question One	Establish other potential scenarios e.g. ash clouds, road closures…	Policy	Real Time	Scenarios
Group B	Question One	Contact neighbouring districts - how can they help.	Policy	Inter-disciplinary	Communications
Group B	Question One	Heightened communications.	Policy	Inter-disciplinary	Communications
Group B	Question Two	Mental health - strain on services.	Policy	Demand-driven (consultancy)	Health
Group B	Question Two	Access to services	Policy	Demand-driven (consultancy)	Critical Infrastructure
Group B	Question Two	Potable water quality - maintenance and performance.	Science	Quality Assessment	Critical Infrastructure
Group B	Question Two	Economic implications e.g. dairy industry.	Policy	Demand-driven (consultancy)	Economic
Group B	Question Two	Resource intensive (people and economics)	Science	Supply-driven (autonomy)	Economic
Group B	Question Two	Power and transport disruptions.	Policy	Demand-driven (consultancy)	Critical Infrastructure
Group B	Question Three	Interdependencies	Policy	Inter-disciplinary	Critical Infrastructure
Group B	Question Three	Contingency plans for various scenarios.	Policy	Applied Science	Planning/Preparedness
Group B	Question Three	Knock-on effects to adjacent districts, industry…	Policy	Inter-disciplinary	
Group B	Question Three	Communication protocols and educating community.	Policy	Inter-disciplinary	Communications
Group B	Question Three	Preparing community for what they need to do.	Policy	Inter-disciplinary	Planning/Preparedness
Group B	Question Three	Long range weather forecasts e.g. ash cloud direction.	Science	Basic Science	Hazard Information and Forecasts

Group C	Question One	GEMO: response and recovery team established.	Policy	Timely Process	Response/Decisions
Group C	Question One	WRC (regional resilience team) work with GNS, CDEM, and TPC to get out consistent messaging to public and build a cleaner picture of event.	Policy	Inter-disciplinary	Communications
Group C	Question One	Work with Mercury (FIDC) to manage lake levels and changes to flood and erosion risk.	Policy	Inter-disciplinary	Communications
Group C	Question One	Health: coordinate psychological response and, in particular, messaging on self-mental health (anxiety) care.	Policy	Timely Process	Health
Group C	Question One	Generators; watching brief and respond as appropriate.	Science	Quality Assessment	Response/Decisions
Group C	Question One	Distribution network and transmission	Science	Disciplinary	Critical Infrastructure
Group C	Question One	Seek advice on potential range of scenarios.	Science	Uncertain, complex information	Scenarios
Group C	Question One	Prepare/revise response plans.	Policy	Applied Science	Planning/Preparedness
Group C	Question Two	Distract from other CDEM work.	Science	Disciplinary	Response/Decisions
Group C	Question Two	WRC more work	Science	Disciplinary	Response/Decisions
Group C	Question Two	Office in Taupo may be affected	Policy	Real Time	Response/Decisions
Group C	Question Two	Would need to put more resource into Taupo, which could take it away from other areas.	Policy	Demand-driven (consultancy)	Response/Decisions
Group C	Question Two	Health: loss of medical staff in hospitals, GPs, Pharmacies, Rest-homes resulting in loss of healthcare resources.	Policy	Demand-driven (consultancy)	Health
Group C	Question Two	Potential lake shore flooding SW of Lake Taupō (Turangi etc).	Science	Basic Science	Hazard Information and Forecasts
Group C	Question Two	Unrest period should not greatly affect electrical networks.	Science	Supply-driven (autonomy)	Critical Infrastructure
Group C	Question Two	Distribution network; potential for damage to network and outages from initial earthquake.	Policy	Real Time	Critical Infrastructure
Group C	Question Two	Repair could be extended (several months) for substations affected especially by shaking or liquefaction.	Policy	Timely Process	Critical Infrastructure

Group C	Question Two	Indirect - Economic impact if large evacuation occurs.	Policy	Demand-driven (consultancy)	Economic
Group C	Question Two	Transmission Grid; potential loss of pylon towers, especially in Waihi area.	Policy	Applied Science	Critical Infrastructure
Group C	Question Two	Could result in generation constraints but unlikely to cause widespread outages.	Science	Supply-driven (autonomy)	Critical Infrastructure
Group C	Question Two	General for all local organisations; loss of personal due to self-evacuation.	Policy	Demand-driven (consultancy)	Evacuation
Group C	Question Three	Scientific knowledge - decisions.	Science	Basic Science	Hazard Information and Forecasts
Group C	Question Three	WRC; Information on earthquake sequence, geothermal changes, deformation, potential options for future.	Science	Basic Science	Hazard Information and Forecasts
Group C	Question Three	Health; communication of clear messages with accurate and easily understood facts.	Policy	Simple Information	Health
Group C	Question Three	Lifelines organisations; range of outcomes and likelihoods populated on a decision-tree to assit in preparing response plans.	Science	Uncertain, complex information	Critical Infrastructure
Group D	Question One	First Gas; Increasing monitoring all gas mains in the area (Taupo).	Science	Quality Assessment	Response/Decisions
Group D	Question One	Helicopters standby	Science	Supply-driven (autonomy)	Response/Decisions
Group D	Question One	NZTA; increase NOC monitoring to SH1 and SH32.	Science	Quality Assessment	Response/Decisions
Group D	Question One	Review status/condition of all SH detour routes.	Science	Quality Assessment	Planning/Preparedness
Group D	Question One	Set up internal and external communications - all key stakeholders.	Policy	Inter-disciplinary	Communications
Group D	Question One	Fuel (Z); Look at supply lines and continuity.	Science	Quality Assessment	Response/Decisions
Group D	Question One	Consider refuelling regimes and extra fuel to main less vulnerable stations.	Science	Long Term	Planning/Preparedness
Group D	Question One	Taupo District Council; Bringing together key information for residents - communications	Policy	Inter-disciplinary	Communications
Group D	Question One	Emergency management teams activated.	Policy	Inter-disciplinary	Response/Decisions

Group D	Question One	Monitoring of water and wastewater systems - more regular.	Science	Quality Assessment	Response/Decisions
Group D	Question One	Potential for wave action issues along the lake edges.	Science	Basic Science	Hazard Information and Forecasts
Group D	Question One	PoT; Mainly BAU.	Science	Disciplinary	Response/Decisions
Group D	Question One	Keep informed.	Policy	Inter-disciplinary	Communications
Group D	Question Two	NZTA; preparations for possible closures of SH1 and SH32.	Policy	Timely Process	Planning/Preparedness
Group D	Question Two	First Gas; Being prepared and assess risks of gas line ruptures near Taupo.	Science	Quality Assessment	Planning/Preparedness
Group D	Question Two	TDC: Review or develop evacuation plans for all lake edge communities.	Policy	Applied Science	Evacuation
Group D	Question Two	Decline in Tourism - economic impacts.	Policy	Demand-driven (consultancy)	Economic
Group D	Question Two	Fuel(Z); Assessing risks at individual stations.	Science	Quality Assessment	Critical Infrastructure
Group D	Question Two	Z consider reduced supply or closure of some stations (Z, Caltex, Challenge).	Science	Long Term	Critical Infrastructure
Group D	Question Two	Consider/implement "purchase order" system for major customers.	Science	Long Term	Critical Infrastructure
Group E	Question One	70% assets below ground core network.	Science	Basic Science	Critical Infrastructure
Group E	Question One	30% assets distribution below ground.	Science	Basic Science	Critical Infrastructure
Group E	Question One	Minimal physical damage but, manageable at this stage.	Policy	Real Time	Critical Infrastructure
Group E	Question One	Investigating the use of alternative network pathways; to maintain same to other centres as well as Taupo.	Policy	Applied Science	Planning/Preparedness
Group E	Question One	Could see the delay to capital projects.	Policy	Demand-driven (consultancy)	Planning/Preparedness
Group E	Question One	Instead increase maintenance or monitoring (geo-tech).	Policy	Demand-driven (consultancy)	Response/Decisions
Group E	Question Two	Could see planned projects bought forward - change of priorities.	Policy	Demand-driven (consultancy)	Planning/Preparedness
Group E	Question Two	Potential in the long-tern for reduction in service if populations migrate (demand reduced).	Policy	Demand-driven (consultancy)	Planning/Preparedness

Group E	Question Two	Unlikely that business would be negatively impacted due to staff affected living in the area.	Policy	Real Time	Economic
Group E	Question Two	Short-term; rise in demand for information from people living through unrest.	Policy	Inter-disciplinary	Communications
Group E	Question Two	Wanting information through internet.	Policy	Inter-disciplinary	Communications
Group E	Question Two	Unrest would become the "new norm".	Science	Long Term	
Group E	Question Two	Some people may leave initially due to uncertainty but after that people are quick to adapt.	Policy	Real Time	Evacuation
Group E	Question Two	Permanent repairs vs. temporary as a result of forecast aftershocks/unrest.	Science	Long Term	Planning/Preparedness
Group E	Question Three	To hear from other utilities (interdependencies) and how they are tackling the uncertainty and physical changes.	Policy	Inter-disciplinary	Communications
Group F	Question One	Lake level rise implications on the control gates at Taupo; power generator, water supplies, flooding risk.	Policy	Applied Science	Critical Infrastructure
Group F	Question One	Wairakei - geothermal activities.	Science	Basic Science	Hazard Information and Forecasts
Group F	Question One	Change in lake level - lower output to Waikato, decrease generation capability.	Policy	Real Time	Critical Infrastructure
Group F	Question One	Increasing monitoring, clearances of floodgates, usual inspections.	Policy	Real Time	Response/Decisions
Group F	Question One	Look at black swan scenarios.	Science	Uncertain, complex information	Scenarios
Group F	Question One	Brush up on contingency plans, review scenarios;	Policy	Applied Science	Scenarios
Group F	Question One	What is looking the same? What is looking different?	Policy	Real Time	Planning/Preparedness
Group F	Question One	Review fuel supplies and back-up resources.	Policy	Applied Science	Response/Decisions
Group F	Question One	Cyber-security.	Policy	Applied Science	Response/Decisions
Group F	Question One	Transpower take lead on 'readiness' group.	Science	Disciplinary	Response/Decisions

Group F	Question Two	Potential for seiching more likely.	Science	Basic Science	Hazard Information and Forecasts
Group F	Question Two	Effect of ground deformation on infrastructure.	Policy	Applied Science	Hazard Information and Forecasts
Group F	Question Two	Impact on transmission stations.	Policy	Applied Science	Critical Infrastructure
Group F	Question Two	Continue to operate as a BAU unless significant impacts.	Policy	Real Time	Response/Decisions
Group F	Question Two	Be aware that there may be more issues, pop-up.	Science	Long Term	Planning/Preparedness
Group F	Question Two	"New normal" operating - automated technology.	Policy	Real Time	
Group F	Question Two	Consideration of changes in 5 year plan.	Science	Long Term	Planning/Preparedness
Group F	Question Two	At what point would we look at building resilience; e.g. parallel network.	Policy	Timely Process	Trigger Points
Group F	Question Two	Resource consents.	Policy	Applied Science	Planning/Preparedness
Group F	Question Two	Implications of increased operating costs are significant.	Policy	Real Time	Economic
Group F	Question Three	What are the potential future scenarios?	Science	Uncertain, complex information	Scenarios
Group F	Question Three	Need backing from support agencies to spend $$.	Policy	Inter-disciplinary	Economic
Group F	Question Three	Credibility around scenario likelihood.	Science	Quality Assessment	Scenarios
Group F	Question Three	Push for resistance building from CDEM is helpful to support readiness requirements.	Policy	Inter-disciplinary	
Group G	Question One	If water rises, will start to lower lake down the line.	Policy	Applied Science	Response/Decisions
Group G	Question One	Repair roads	Policy	Applied Science	Response/Decisions
Group G	Question One	Ensure alternative routes are available.	Policy	Timely Process	Planning/Preparedness
Group G	Question One	Speed up investment in Taupo control gate structure.	Policy	Demand-driven (consultancy)	Planning/Preparedness
Group G	Question One	Displaced affected people and welfare support.	Policy	Demand-driven (consultancy)	Evacuation
Group G	Question Two	Shut down (or limit) power generation.	Policy	Applied Science	Response/Decisions

Group G	Question Two	Impact on flooding infrastructure e.g. flood-banks (dams).	Policy	Applied Science	Critical Infrastructure
Group G	Question Two	Increase maintenance cost.	Policy	Demand-driven (consultancy)	Economic
Group G	Question Two	Road closed will have disruption to communities.	Policy	Real Time	Critical Infrastructure
Group G	Question Two	Potential future changes.	Science	Long Term	Planning/Preparedness
Group G	Question Two	Power prices will go up over a short period (short-term).	Policy	Demand-driven (consultancy)	Economic
Group G	Question Two	Hydrology changes over the long run (long-term).	Science	Long Term	Response/Decisions
Group G	Question Two	Recovery	Policy	Timely Process	Response/Decisions
Group G	Question Two	Time of the recovery period.	Policy	Real Time	Response/Decisions
Group G	Question Two	Who is going to lead the recovery (National/Regional/Local)?	Policy	Inter-disciplinary	Response/Decisions
Group G	Question Three	Lake Changes	Science	Basic Science	Hazard Information and Forecasts
Group G	Question Three	The change in the level of the lake	Science	Basic Science	Hazard Information and Forecasts
Group G	Question Three	Temperature of the lake	Science	Basic Science	Hazard Information and Forecasts
Group G	Question Three	The runoff does not run into lake due to lake rise (pumps).	Policy	Simple Information	Critical Infrastructure
Group G	Question Three	Ground deformation	Science	Basic Science	Hazard Information and Forecasts
Group G	Question Three	Forecast position of land movement.	Science	Uncertain, complex information	Hazard Information and Forecasts
Group G	Question Three	Extent of uplift and direction of movement.	Science	Uncertain, complex information	Hazard Information and Forecasts
Group G	Question Three	Economic impact on Taupo.	Policy	Demand-driven (consultancy)	Economic

Group H	Built Environment	Ashfall	Science	Basic Science	Hazard Information and Forecasts
Group H	Built Environment	Earthquakes affecting distribution.	Policy	Applied Science	Critical Infrastructure
Group H	Built Environment	Real Estate.	Policy	Applied Science	Economic
Group H	Built Environment	Roads.	Policy	Applied Science	Critical Infrastructure
Group H	Economic Environment.	Mercury	Science	Disciplinary	Economic
Group H	Economic Environment.	Lakes	Science	Basic Science	Economic
Group H	Economic Environment.	Loss in Tourism	Policy	Applied Science	Economic
Group H	Social Environment	Lakes DHB	Science	Disciplinary	Health
Group H	Social Environment	Evacuation	Policy	Demand-driven (consultancy)	Evacuation
Group H	Social Environment	Psychological impacts	Policy	Demand-driven (consultancy)	Health
Group H	Social Environment	Hospital staffing	Policy	Demand-driven (consultancy)	Evacuation
Group H	Natural Environment	WRC	Science	Disciplinary	
Group H	Natural Environment	Lake/water management	Science	Basic Science	Planning/Preparedness
Group H	Natural Environment	Slips/land movement (Waihi).	Science	Basic Science	Hazard Information and Forecasts
Group I	Question One	_____ an early communication piece that needs to be integrated across local government, central government, lifelines, and media.	Policy	Inter-disciplinary	Communications
Group I	Question One	The people need (and want) to know and the advantage of this situation is that it has been brewing for a long time.	Policy	Inter-disciplinary	Communications

Group I	Question One	And the message across all invested stakeholders needs to be consistent.	Policy	Inter-disciplinary	Communications
Group I	Question One	There will be some pre-event contingency planning that everyone will be doing	Policy	Applied Science	Planning/Preparedness
Group I	Question One	And perhaps this would see an increased monitoring regime.	Policy	Real Time	Planning/Preparedness
Group I	Question One	And if also needs the credible scenario mentioned below.	Science	Quality Assessment	Scenarios
Group I	Question Two	There's an uncertainty piece and this needs to be managed	Science	Uncertain, complex information	Hazard Information and Forecasts
Group I	Question Two	____ means that on decision(s)	Policy	Applied Science	Response/Decisions
Group I	Question Two	Regarding stay or go	Policy	Real Time	Evacuation
Group I	Question Two	Regarding preparations and planning.	Policy	Applied Science	Planning/Preparedness
Group I	Question Two	Regrading triggers for eventual evacuating.	Policy	Demand-driven (consultancy)	Trigger Points
Group I	Question Two	Regarding enhanced monitoring and inspections.	Policy	Real Time	Response/Decisions
Group I	Question Two	All need to be made an all key players need to have input into this decision.	Policy	Inter-disciplinary	Communications
Group I	Question Two	And the framework for making these decisions and who is making these decisions needs to be understood by all.	Policy	Inter-disciplinary	Planning/Preparedness
Group I	Question Three	A credible scenario	Science	Quality Assessment	Scenarios
Group I	Question Three	The triggers for evacuation or future decisions.	Policy	Real Time	Trigger Points
Group I	Question Three	That need to be shared with the public and then the public will need to know if the triggers have been met following an event(s).	Policy	Inter-disciplinary	Communications
Group I	Question Three	An understanding of who is leading the overall contingency planning/response planning and how individual agencies feed into it.	Policy	Inter-disciplinary	Planning/Preparedness
Group I	Question Three	An i____ is how much time/effort/money is spent and developing plans or preparing.	Policy	Demand-driven (consultancy)	Planning/Preparedness

Group I	Question Three	An additional ____ is that we're talking a slow-burn, gradual escalation that's occurring here and it can be hard to anticipate enthusiasm/willingness for planning and preparation over a suspended time.	Science	Uncertain, complex information	Planning/Preparedness

Appendix E ECLIPSE SCENARIO FRAMEWORK EVALUATION INTERVIEWS

E.1 ETHICS APPROVAL

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2019/162

9 December 2019

Geena Campbell
Earth and Environment
UNIVERSITY OF CANTERBURY

Dear Geena

The Human Ethics Committee advises that your research proposal "Hazard and Impact Scenario Development for Silicic Volcanoes in New Zealand" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 4th December 2019.

Best wishes for your project.

Yours sincerely

Dr Dean Sutherland
Chair
University of Canterbury Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

F E S

Appendix Figure E.1: Letter of Approval from the Human Ethics Committee for Ethical research within the ECLIPSE Scenario Framework Evaluation Interviews.

E.2 ECLIPSE Scenario Framework Evaluation Interviews Questionnaire

ECLIPSE Scenario Framework Questionnaire

School of Earth and Environment
Department of Geological Sciences.
Disaster Risk Resilience.
Telephone: +64 3 364-2987 ext. 94503
Email: geena.campbell@pg.canterbury.ac.nz

ECLIPSE

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Hazard and Impact Scenario Development for Silicic Volcanoes in New Zealand.

Organisation Name:

Your role within your organisation:

1. **What is your organisation's role, and responsibilities, in New Zealand's volcanic disaster risk management?**
   This can be both in non-crisis and during crisis.

2. **How would your organisation use the scenario?**
   List as many ways as you feel is applicable, then rank these applications (this can be done in groups of most to least important – however, you do not have to scale importance up/down if you feel all the uses belong in one category, i.e. most important).

3. **How useful and useable is the scenario for your organisations roles and responsibilities?**
   Previous engagements throughout this project identified factors and aspects that your organisation identified as important for the use of scenarios, which have helped inform the scenario's development.

   Is there anything missing? Such as factors or aspects that have since been identified as more, or less, important?

4. **Would your organisation use the scenario framework to create your own scenario(s)?**

5. **For your organisation, what would be useful guidance for the use of the scenario framework?**

6. **Would having a common suite of scenarios, accommodating different applications, be useful? If so, how might that be useful?**

--- End of Questionnaire ---

Geena Campbell

Appendix Figure E.2: ECLIPSE Scenario Framework Evaluation Interviews questionnaire provided to participants.

Appendix F HISTORICAL CALDERA EVENTS

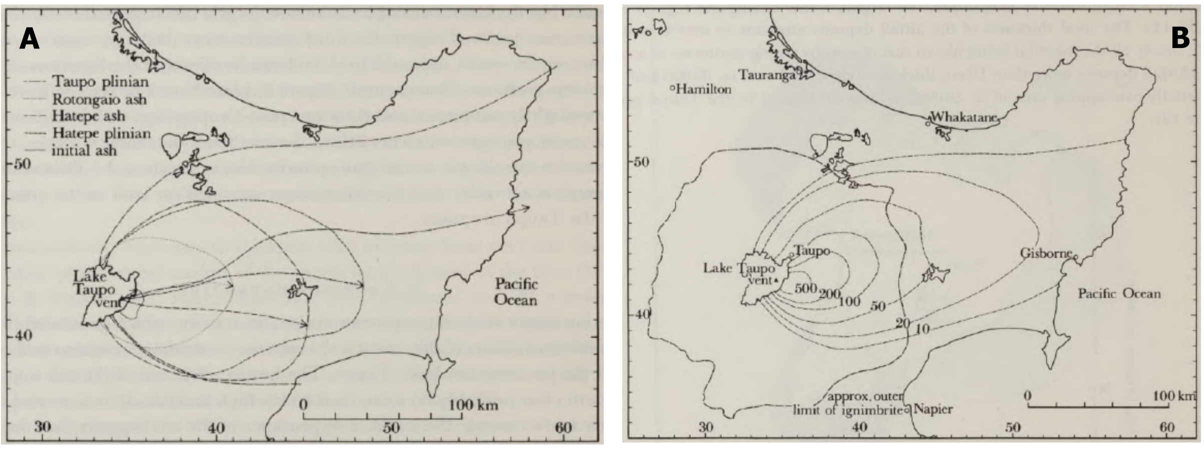
This appendix details the historical events at caldera around the world that were used to inform and model the ECLIPSE Scenarios; Scenario A: Taupō Unrest Scenario (*Chapter 4, Section 4.1*) and Scenario B: Taupō Eruption Scenario (*Chapter 4, Section 4.2*).

F.1 TAUPŌ VOLCANIC CENTRE, AOTEAROA-NEW ZEALAND

F.1.1 Taupō Caldera 186 AD Eruption

The most recent eruption from the TVC, and one of the largest explosive eruptions in the world within the past 7,000 years, occurred around 1,800 years ago from a vent within the Horomatangi Reefs in modern day Lake Taupō (Wilson & Walker, 1985ab).

The eruption began with minor phreatomagmatic activity, followed by a Plinian outburst from the dry vent. Following this, large quantities of water entered the vent during a phreatoplinian ash phase, eventually stopping the eruption, however, large amounts of water continued to be ejected from the vent area – termed "water-spouting" – causing gullying through already deposited ash. This was followed by a break in eruptive activity for several hours to weeks with phreatoplinian activity resuming after, generating more ash (*Figure F.1a*; Wilson & Walker, 1985a). The vent again became dry with the eruption rate and power increasing into the most powerful Plinian outburst yet. Simultaneously, partial collapse of the eruption column caused small pyroclastic flows to travel northeast. Furthermore, because the magma driving the previous phases of eruption was removed rapidly, the vent area lost support and local vent collapse was triggered.



*Appendix Figure F.1: **A:** Ash fall dispersal pattern deposits from the "Taupō Eruption" with the inferred wind direction (arrow) drawn along each dispersal axis. **B:** Eastern central North Island with isopachs of total ash fall* *thickness (in centimetres) at the cease of the eruption. The area covered by the final pyroclastic flows, "Taupō ignimbrite" is also shown (Wilson & Walker, 1985a).*

This initiated the devastating "Taupō ignimbrite" pyroclastic flows (*Figure F.1b*) that travelled radially out from the Lake Taupō vent covering approximately 20,000km^2 in area (Wilson & Walker, 1985ab).

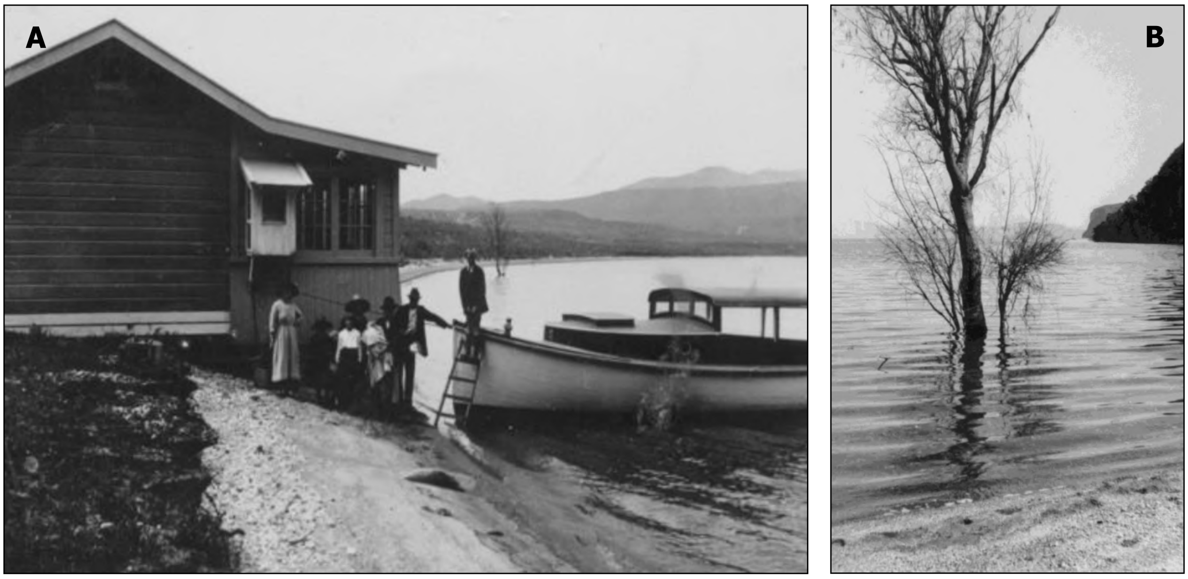
Post-eruption, local severe ground shaking occurred associated with subsidence in the Lake Taupō basin, with more widespread ground shaking triggering degassing within the pyroclastic flow deposits. Some of this degassing may have triggered phreatic explosions where water flashed to steam and ejected already deposited material on the surrounding pyroclastic flow deposits (Wilson & Walker, 1985a). Mudflows (lahars) and more dilute muddy-flood deposits also extended for tens of hundreds of kilometres beyond the pyroclastic flow deposit limits, likely deposited by catastrophic flooding on all rivers draining the central North Island. These more frequently occurred in the first few hours to months post-eruption, however, subsequent mudflows may have continued for years to decades (Wilson & Walker, 1985a).

F.1.2 Taupō Volcanic Centre April 1922 to January 1923 Unrest Episode

From April 1922 to January 1923, the Taupō Volcanic Centre (TVC) experienced the largest episode of caldera unrest known to have occurred in A-NZ during historical time without a subsequent eruption (Potter, Scott & Jolly, 2012). Earthquakes, migrating north to south, were felt throughout the Taupō district resulting in landslides (*Figure F.2*) blocking roads, several chimneys collapsing, household contents being thrown to the floor, and the Taupō town clock stopping (Potter, Scott & Jolly, 2012).

Appendix Figure F.2: Landslide from Taupō earthquake swarm (Gerard Ward Collection, Taupō Museum).

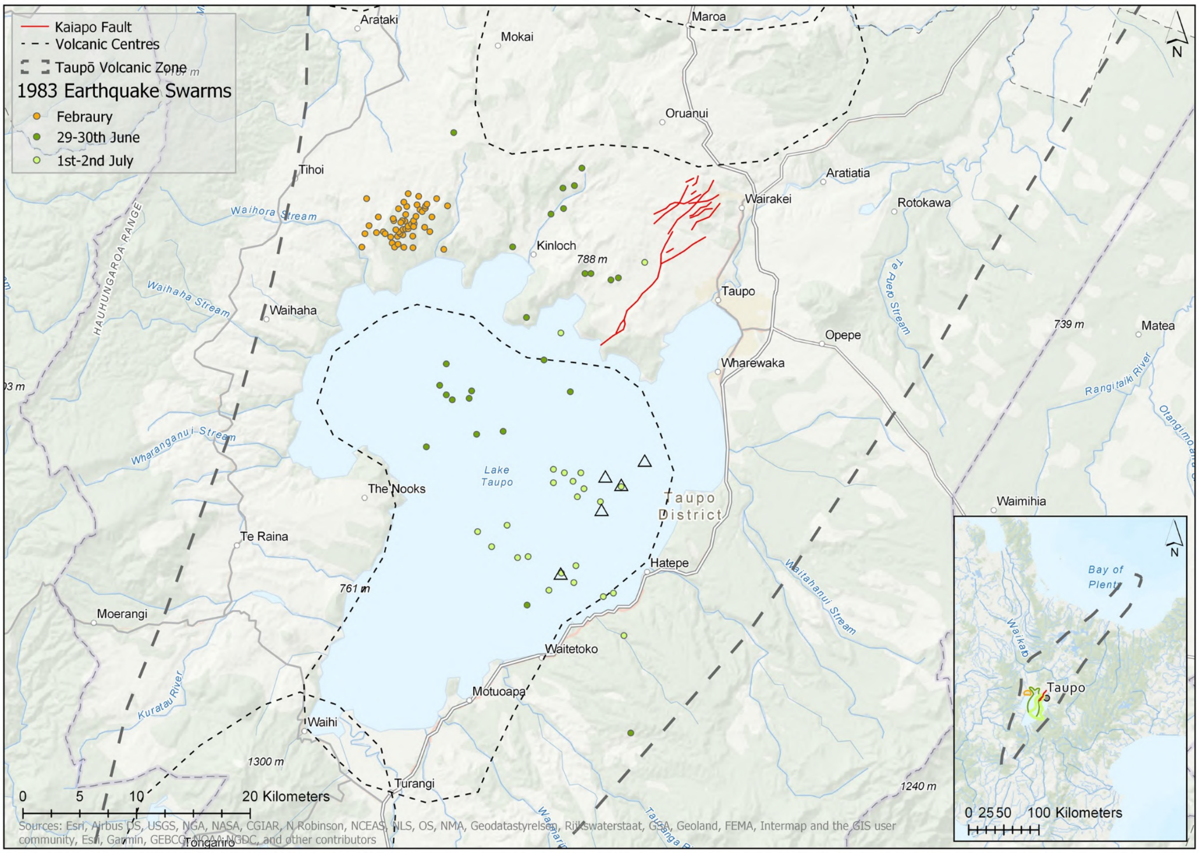
3.7m of subsidence, along the northern edge of Lake Taupō, caused a sunken shoreline at Whakaipo Bay (*Figures F.3ab*), resulting in hundreds of water fountains emerging from ground cracks, causing flooding. Fissuring, faulting and minor changes to activity at hot springs and geysers were also reported. Voluntary evacuations occurred and tourism was impacted in Taupō and Rotorua due to incorrect international reporting (Potter, Scott & Jolly, 2012).



*Appendix Figure F.3: **A:** flooding caused by subsidence at Whakaipo Bay, 1922 **B:** Flooding caused by subsidence at Whakaipo Bay, 1922 (Gerard Ward Collection, Taupō Museum).*

F.1.3 Taupō Volcanic Centre February 1983 to December 1984 Unrest Episode

Another significant period of caldera unrest occurred in the TVC from February 1983 to December 1984. Unrest began with an earthquake swarm to the northwest of Lake Taupō, 6km west-northwest of Kinloch, at 4-8km depth, covering a 30km^2 area (*Figure F.4*; Newhall & Dzurisin, 1988; Webb, Ferries & Harris, 1986; Potter et al., 2015b). The February swarm started abruptly, was active for 10 days, then continued at a lower level of activity for another 50 days. The swarm consisted of three large (M_w3.7) events and moderate shaking intensities were reported (Webb, Ferries & Harris, 1986). From March to June 1983 the northern shore of Lake Taupō uplifted 5.7cm and a hydrothermal eruption occurred at the Wairakei geothermal field on 19th April 1983 (Newhall & Dzurisin, 1988; Potter et al., 2015b).



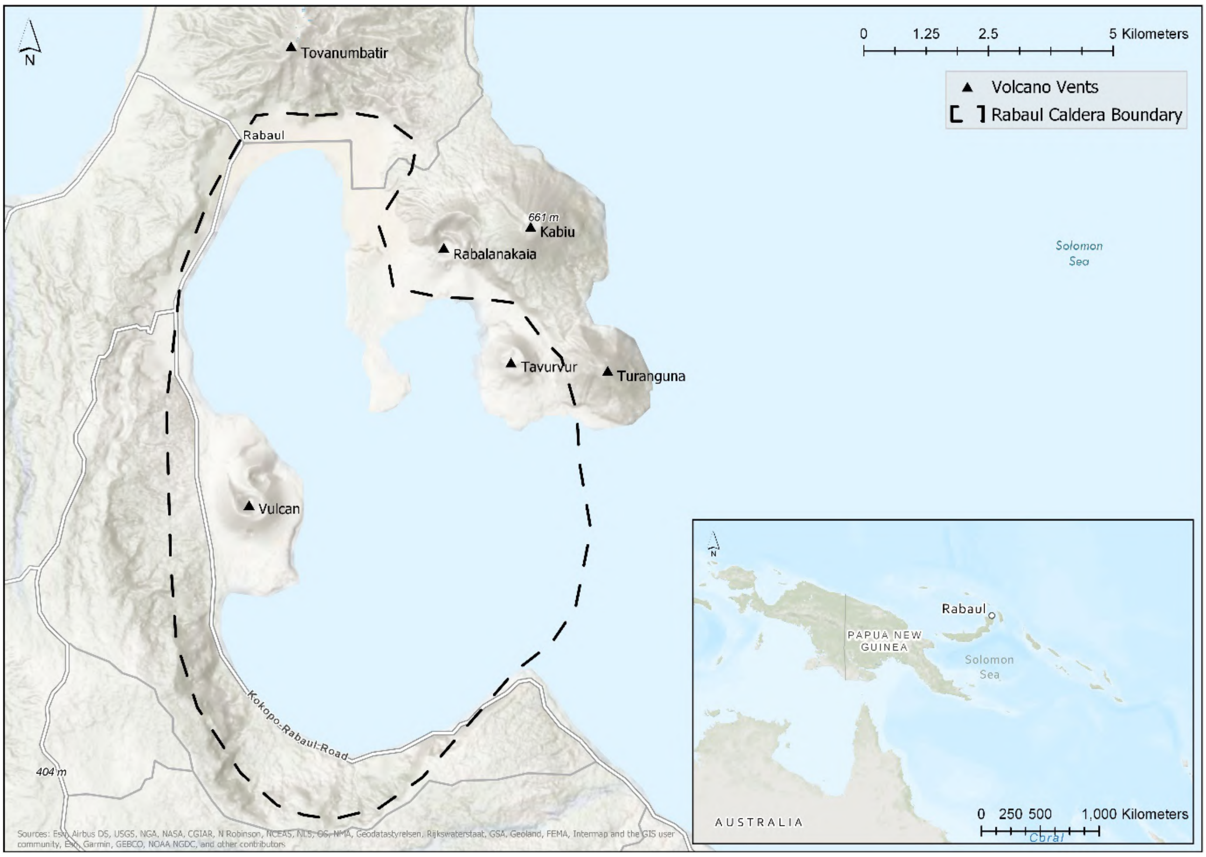
Appendix Figure F.4: February, July and June 1983 earthquake swarms in the Taupō district area (derived from Webb, Ferries & Harris, 1986).

Throughout June and July 1983, several phenomena occurred to further the unrest. On 16th June, a new, stronger, earthquake swarm (<M_W4.3) occurred and rapid subsidence follow on the northwest of the Kaiapo Fault (*Figure F.4*; Newhall & Dzurisin, 1988). Another swarm centred near Kaiapo Bay peaked in intensity on 20th-21st June, with over 30 earthquakes per day. Tension cracks also formed and moderate shaking intensities were reported (Potter et al., 2015b). On 23rd June 1983, the Kaiapo Fault ruptured, with 1.2km of displacement and 43mm of subsidence on the western side of the fault. The rupture resulted in minor damage to household contents and chimneys (Potter, Scott & Jolly, 2012; Potter et al., 2015b). Another earthquake swarm occurred on 19th-30th June, swiftly followed by another on 1st-2nd July 1983 (Webb, Ferries & Harris, 1986). A possible volcanic earthquake was also recorded on the 2nd July and the western side of the Kaiapo Fault increased in subsidence from 43mm to 55mm (Potter et al., 2015b). The late June, early July earthquake swarms started and ended abruptly, with most of the activity centred under Lake Taupō. The activity showed a northern migration with time, with a sudden reoccurrence of activity to the south near the end of the swarms. Shaking was felt less than the February swarms, likely due to the epicentre locations being under the Lake, further from populations (Webb, Ferries & Harris, 1986). Further small, localised earthquake swarms were felt on 4th August, 20th September, 4th October 1983 and February and March 1984 (Potter et al., 2015b). In late 1984, the northeast shore of Lake Taupō experienced 1-1.5cm of uplift (Newhall & Dzurisin, 1988).

F.2 RABAUL CALDERA, PAPUA NEW GUINEA

F.2.1 Rabaul Caldera 1970s to 19802 Unrest Episode

Rabaul caldera, located on the eastern end of New Britain Island in Papua New Guinea (*Figure F.5*), has experienced both very large and relatively small eruptions and frequent unrest throughout its lifetime (Potter, Scott & Jolly, 2012).



Appendix Figure F.5: Location of the Rabaul caldera, the Tavurvur and Vulcan vents, and Rabaul city in Papua New Guinea (derived from Le Blond et al., 2010).

Throughout the 1970s and 1980s, Rabaul experienced significant unrest behaviour. The unrest episode began with two large (M_w8.0) earthquakes in the Solomon Sea (130km and 230km from Rabaul) in 1971, after which changes in the geologic environment at Rabaul were noted (Newhall & Dzurisin, 1988; Potter, Scott & Jolly, 2012). This unrest activity escalated in March

1983, possibly in relation to a M_w7.6 earthquake 200km east of Rabaul. Volcanic behaviour at this time typically consisted of hundreds of earthquakes within an hour, with moderate shaking intensity. Prior to November 1971, Rabaul experienced 60 earthquakes per month on average, this increased to 320 earthquakes by August 1983 (Newhall & Dzurisin, 1988). Rabaul also experienced substantial uplift during this unrest, with the average uplift rate at 7cm per month between August 1983 and July 1985, compared to 0.8cm per month for the preceding decade. Overall, 3.5m of total uplift occurred between 1971 and 1984 (Newhall & Dzurisin, 1988; Potter, Scott & Jolly, 2012). This unrest caused some preparedness actions to take place and response plans and legislation were updated (Potter, Scott & Jolly, 2012).

Rabaul caldera would eventually erupt out of the Tavurvur (*Figure F.6a*) and Vulcan vents in September 1994 (*Figure F.6b*). This caused an evacuation of 53,000 people from Rabaul city and surrounding areas and claimed five lives (Potter, Scott & Jolly, 2012; GVP, 2016). Vulcan stopped erupting in October 1994, but Tavurvur continued erupting into 1995. However, Tavurvur has remained intermittently active since ceasing in 1995 (GVP, 2016).

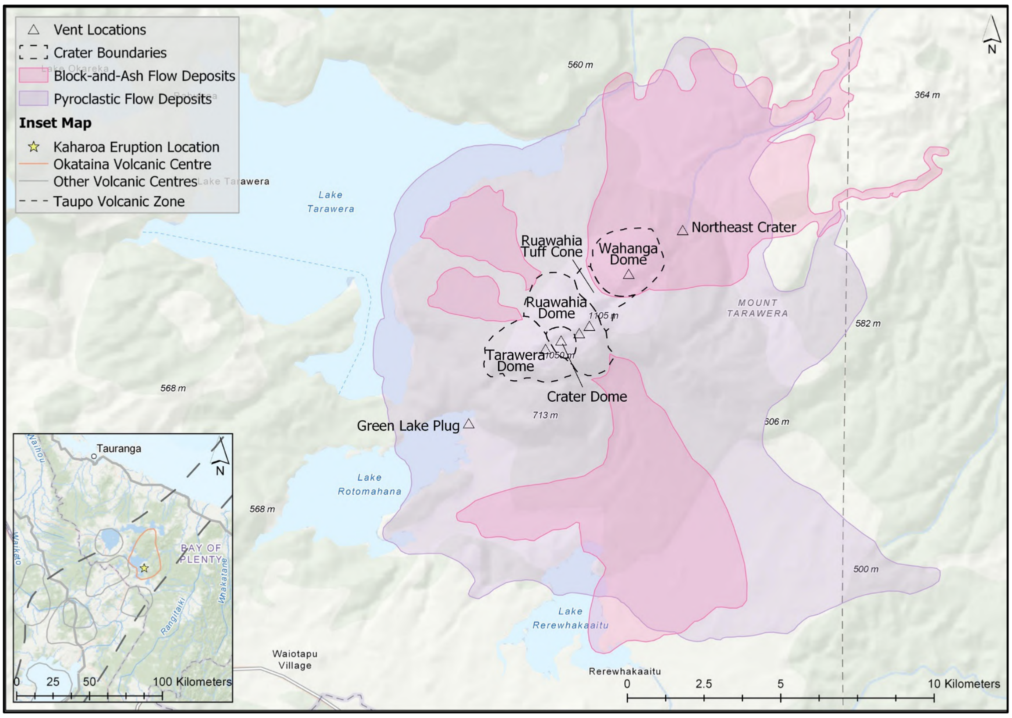
*Appendix Figure F.6: **A:** Tavurvur cent erupting, 1994. **B:** Rabaul city covered in a blanket of ash, 1994 (GVP, 2016).*

F.3 OKATAINA VOLCANIC CENTRE, AOTEAROA-NEW ZEALAND

F.3.1 1314 AD Kaharoa Eruption Event

The Okataina Volcanic Centre (OVC) in A-NZ's North Island is home to the largest eruption to occur in A-NZ in the last 1,000 years, the 1314 AD Kaharoa eruption, erupting more than 4km^3 or rhyolite magma and producing more than 5km^3 of pyroclastic material (Johnston et al., 2000; Johnston, Nairn & Martin, 2002). The eruption occurred from at least seven vents spread along an 8km linear zone (*Figure F.7*) and was likely preceded by a lengthy period of unrest consisting of seismicity and ground deformation (Johnston, Nairn & Martin, 2002).

The eruption began with explosions from the Crater Dome with pyroclastic flows (*Figure F.7*) entering Lake Tarawera, causing a tsunami wave to wash upon the opposite (western) shoreline. Plinian eruptions later occurred from the Ruawahia and Wahanga vents, with this pyroclastics and Plinian phase lasting for a few months. The Ruawahia and Wahanga Domes later partially collapsed after years of dome building activity, generating block-and-ash flows (*Figure F.7*), with gas and steam explosions continuing for some years until cooling in the domes was completed.



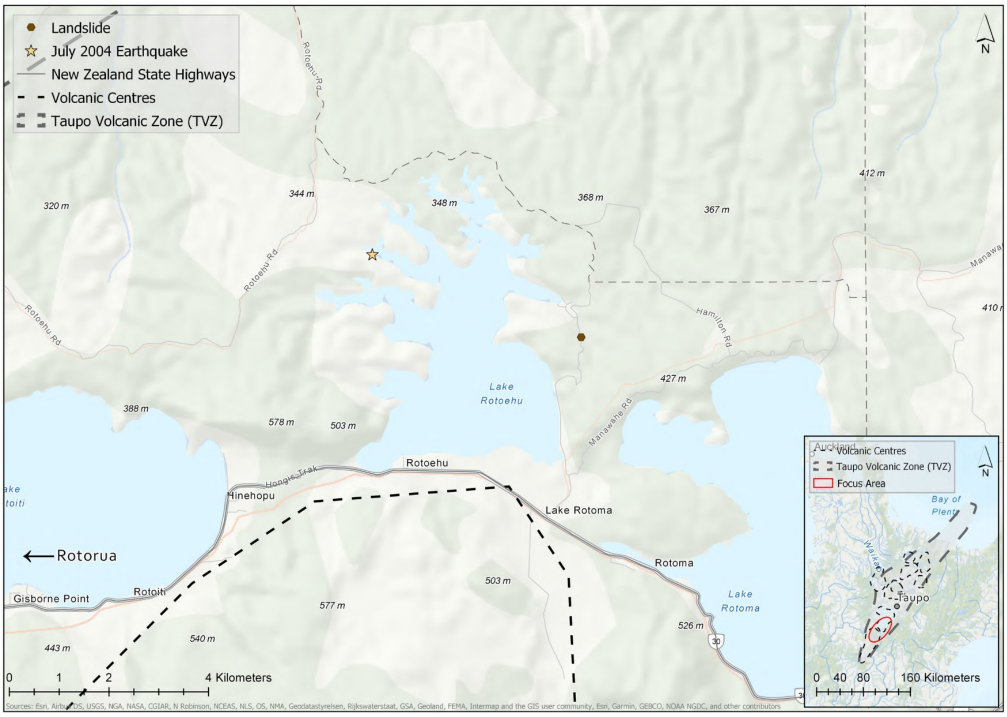
Appendix Figure F.7: 1314 AD Kaharoa Eruption vent and crater locations with pyroclastic and black-and-ash flow deposits (derived from Johnston, Nairn & Martin, 2002).

F.3.2 Lake Rotoehu Earthquake Event

A M_w5.4 earthquake ruptured in the Lake Rotoehu area on Sunday 18th July 2004 (*Figure F.8*; GeoNet, 2004b). The earthquake, located 20km northwest of Kawerau, was felt throughout the Bay of Plenty region and was followed by hundreds of shallow earthquakes (GeoNet, 2004a). At least another five significant earthquakes were big enough to have been felt throughout the region. The earthquake epicentres remained clustered northwest of Kawerau and were determined to be related to long-term tectonic stretching of the area.

This earthquake event caused numerous landslides, particularly on State Highway 30 between Rotorua and Whakatāne (*Figures F.8* and *F.9*; GeoNet, 2004b; New Zealand Herald, 2004).

The event also resulted in school closures the following day. Monday 19th July 2004, as well as one casualty and a few moderate injuries (New Zealand Herald, 2004).

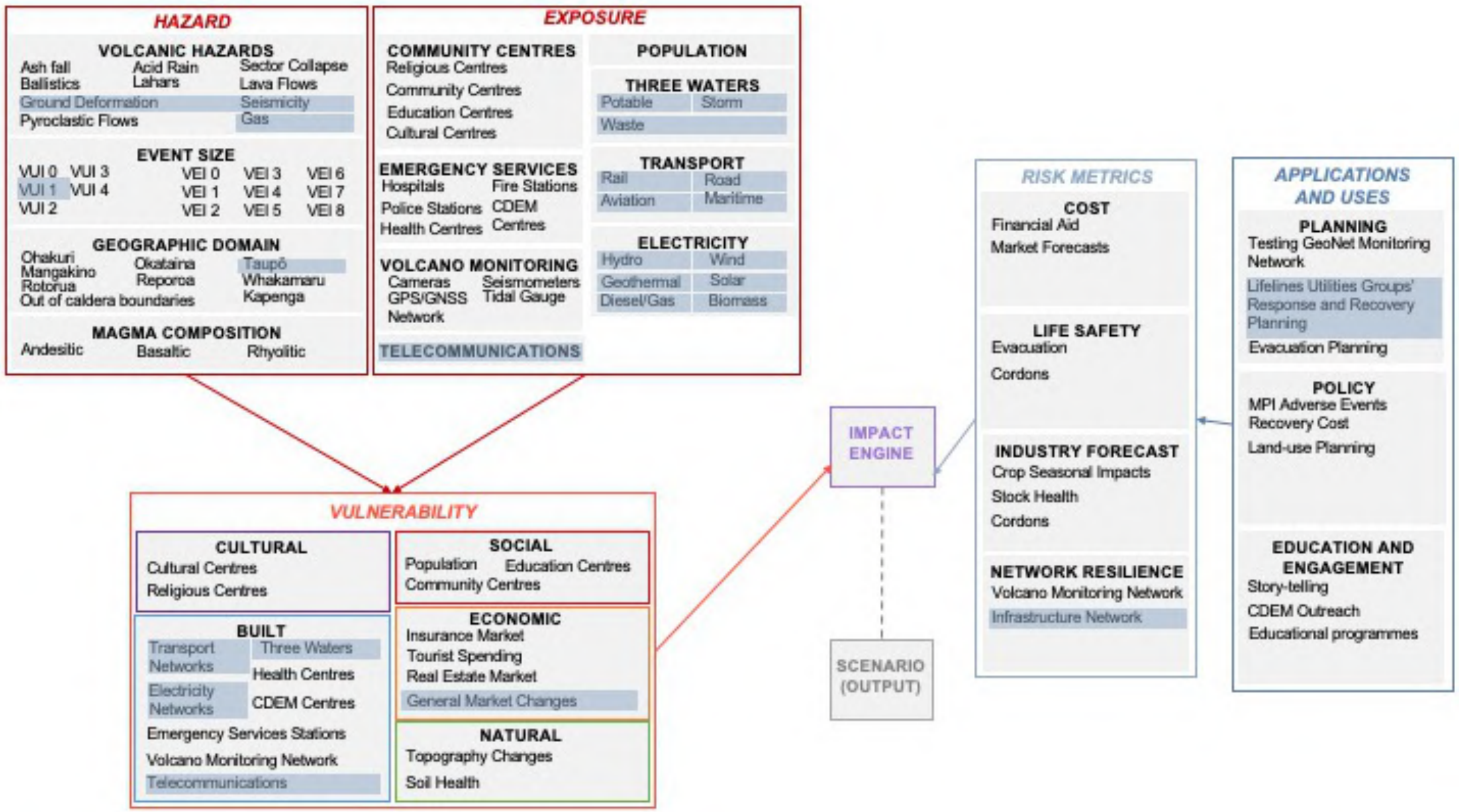


Appendix Figure F.8: July 2004 earthquake epicentre and landslide (shown in Figure F.9 below*) locations within the Okataina Volcanic Centre (derived from GeoNet, 2004b; Hancox et al., 2004).*

Appendix Figure F.9: Ground cracking and landslide on Pongakawa Valley Road as a result of the July 2004 earthquake (Hancox et al., 2004).

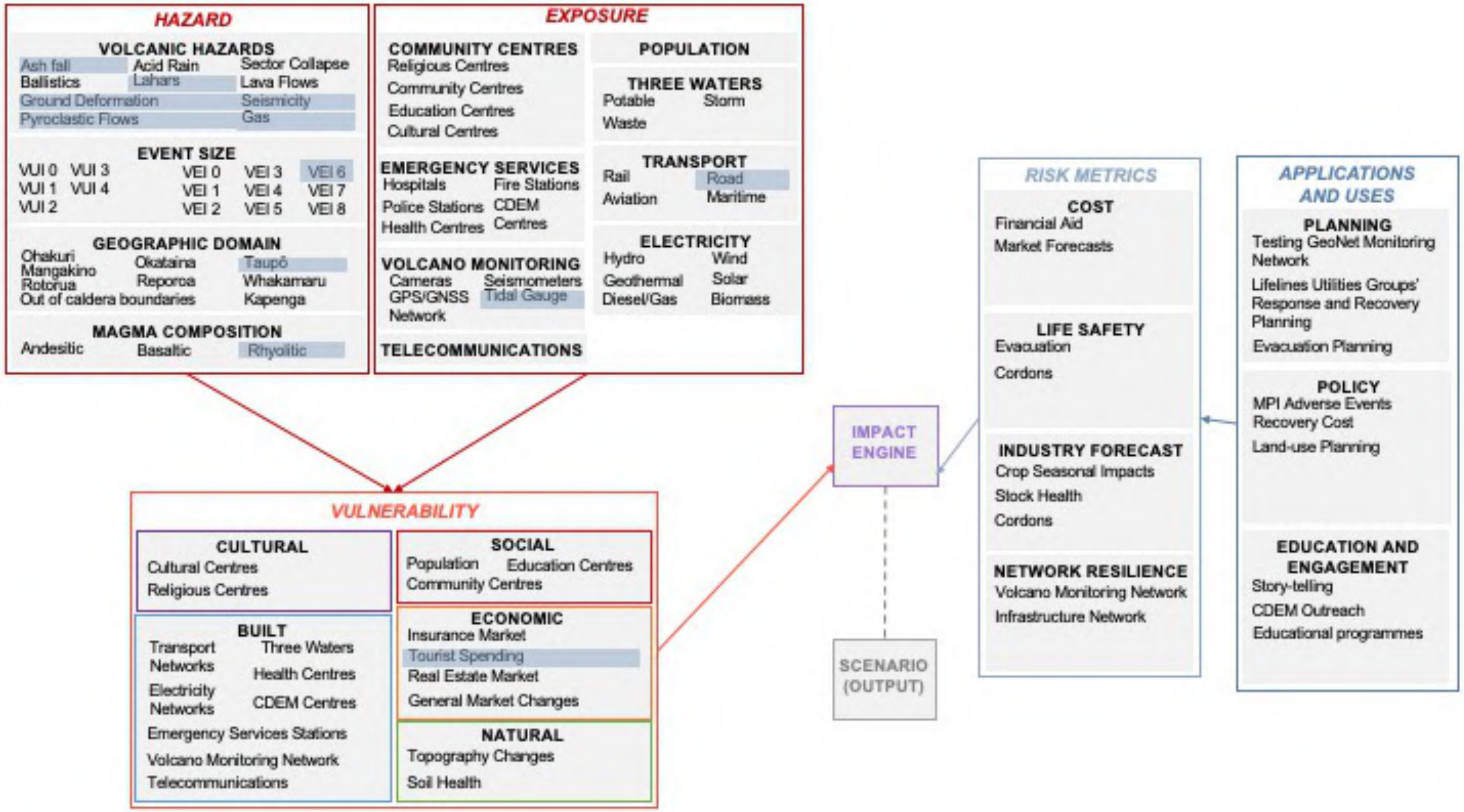
Appendix G ECLIPSE SCENARIO WORKFLOWS

G.1 ECLIPSE SCENARIO A: THE TAUPŌ UNREST SCENARIO



Appendix Figure G.1: The set of attributes selected in the ECLIPSE Scenario Framework to develop ECLIPSE Scenario A.

G.2 ECLIPSE Scenario B: The Taupō Eruption Scenario



Appendix Figure G.2: The set of attributes selected in the ECLIPSE Scenario Framework to develop ECLIPSE Scenario B.